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Flow and Gas Sampling Manual

TRW Systems Group, Redondo Beach, Calif

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16. ABSTRACT The manual summarizes work done on a project to measure volumetric flowrate and composition in gas-phase process streams. It is intended for use by measurement professionals to apply the developed techniques for continuous measurements of volumetric flowrate. Also presented are techniques for extracting a representative gas sample from a process stream. Information is given for selecting the optimum number of sampling points to achieve reasonable accuracy in a cost effective manner.

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FLOW
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SAMPLING MANUAL

by

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FOREWORD

This manual describes techniques used to measure volumetric flow and to extract representative gas samples from process streams. It was prepared under Task 13 of EPA Contract No. 68-02-1412, "Quick Reaction Technical Services in Air Pollution Sampling Acquisition and Analysis, Process Instrumentation, Process Research and Process Evaluation."

This work was conducted under the technical direction of Mr. W. B. Kuykendal, EPA, Task Order Manager, and the administrative direction of Dr. L. D. Johnson, Environmental Research Center, Research Triangle Park, North Carolina. The Advanced Instrumentation Department and Applied Chemistry Department, Applied Technology Division, TRW Systems and Energy, Redondo Beach, California were responsible for the work performed on this program. Dr. E. A. Burns, Manager, Applied Chemistry Department, was Program Manager, and the Task Order Manager was E. F. Brooks. Computer analyses and simulations were performed by R. L. Williams.

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1. INTRODUCTION

This manual deals with current technology for the measurement of total volumetric flow in process stream ducts and for the extraction of representative gas samples. The purpose of the manual is to discuss techniques and hardware to be used to obtain optimum measurement accuracies while minimizing measurement system complexity and labor requirements. Both manual traverses and continuous measurement systems are considered. Modifications to current methods are suggested where applicable, along with the reasoning for the proposed modifications.

The background for the manual was taken from EPA program 68-02-0636, "Measurement Techniques for Control System Evaluation - Total Gas Flow Rate," sponsored by the Process Measurements Branch of the Industrial and Environmental Research Laboratory. Program results are documented in References 1 and 2. This manual was prepared along with a shorter document, "Guidelines for Stationary Source Continuous Gas Monitoring Systems," Reference 3, and under the "Quick Reaction" program cited in the Foreword. Program results indicate that composition and flow measurements in large process stream ducts can be routinely made with accuracies on the order of 5% to 10% on a continuous basis using available hardware and techniques. This represents a significant improvement over commonly accepted accuracies, especially for single point sampling, of 20% to 30%. Secondary program results relative to the accuracy and efficiency of manual measurements have resulted in several suggestions for improvement of standard methods, such as optimization of the number of measurement points for flow measurement and gas sampling.

The manual is organized as follows:

Section 2. Derivation of Equations - To provide a proper framework, flow and gas sampling equations are derived from the basic principle of conservation of mass, and the simplifying assumptions used to produce the final engineering relations are identified.

Section 3. Error Analysis - A standard error analysis is performed on the derived equations and individual error sources are discussed in order

to identify the critical ones. Error sources fall into two broad categories: single point errors are those due to inaccuracies inherent in the instruments used; methodology errors are those due to the inadequacy of sampling schemes to properly account for flow and compositional stratifications and temporal flow variations. Either category may be responsible for the largest system errors. The most critical sources are identified in this section and suggestions as to how to deal with them are given in Sections 4 and 5.

Section 4. Sampling Methodology - Techniques for manual and continuous sampling are presented. The chosen techniques are designed to optimize accuracy, operational efficiency and cost. Evidence is presented to suggest that flow proportional gas sampling is not required, and that the optimum number of sampling points for manual traverses is sixteen. The Row Average Method, using nominally eight measurement points, is recommended for continuous monitoring applications, and single point sampling is found to be generally unacceptable for continuous measurements.

Section 5. Hardware - State of the art velocity measurement instruments are discussed, a need and prototype designs for a multiport continuous gas sampling probe are presented, and a prototype continuous monitoring system is shown. The relative merits of the pitot-static probe and S probe for point velocity measurement are presented, and a clear preference for the pitot-static probe is demonstrated so long as an accurate instrument is used to measure differential pressure.

Section 6. Prototype Continuous Monitoring Procedures - The material from the previous sections is summarized in the form of general procedures for installation and calibration of continuous monitoring systems. This section is a complete unit in itself in that it contains figures, tables, and equations necessary for system implementation.

There have been major improvements in recent years in process stream instrumentation, and several of these are documented in the report. To make full use of these improvements, the techniques for flow measurement in process streams must also be improved. A major purpose of this report is to indicate where commonly used techniques such as the EPA Federal Register methods are potentially inaccurate or impractical, and to suggest modifications to simplify these common procedures and/or make them more accurate.

Discussion of gas sampling is limited to the problem of how to extract a representative gas sample from a process stream. Sample analysis techniques for the extracted sample are very well documented in other sources, such as References 8 and 11. In addition, the growing use of continuous gas analyzers has resulted in a greater emphasis on how to deliver a representative sample to the analyzer.

The manual contains no completely new and radical approaches to the problems of flow and composition measurement, but it does discuss significant and possibly controversial changes to existing procedures. These recommended changes are the end result of extensive testing, both in the laboratory and in the field. Analysis of the accumulated data resulted in the proposed modifications -- it was never the case that a modification was proposed first and then data were found to support it. Also, it is certainly recommended that a broader data base be established for techniques such as spatial gas sampling in order to identify their limitations.

Environmental monitoring is presently the area of greatest application for the technology discussed in this manual. As the accuracy and availability of continuous monitoring instrumentation increase, it is expected that continuous monitors will also find much use in the area of energy conservation, since precise information about process stream conditions can be used to optimize plant operating conditions, thus minimizing fuel and power requirements. The accuracy of a measurement system is a function both of the instruments used and the methods by which they are used. This manual is intended to acquaint the reader with some of the best available hardware for process stream measurements and with methodology developed specifically to make the best use of the hardware.

2. DERIVATION OF EQUATIONS

In this section, the principle of conservation of mass is used to derive process stream flow equations in terms of actual measured parameters. The equations of interest are those for total gas volumetric flowrate, total gas mass flowrate, species gas mass flowrate, and average gas species concentration. Simplifying assumptions used to obtain the final equations are identified. The derived equations serve as a basis for the error analysis presented in Section 3, and as background for Sections 4 and 5.

2.1 CONSERVATION OF MASS-MATHEMATICAL REPRESENTATION

This manual is concerned with measurements in ducted process streams. In all cases, measurements are assumed to be taken in a plane normal to the local duct axis. This will be refered to as the measurement or sample plane and is illustrated in Figure 1. Using the principle of conservation of mass as described in Reference 4, we can represent the net mass flux through the plane as:

$$\dot{m} = \iint_A \rho \vec{u} \cdot \vec{n} \, dA \qquad (1)$$

where

$\dot{m}$ = total mass flow rate, gm/sec

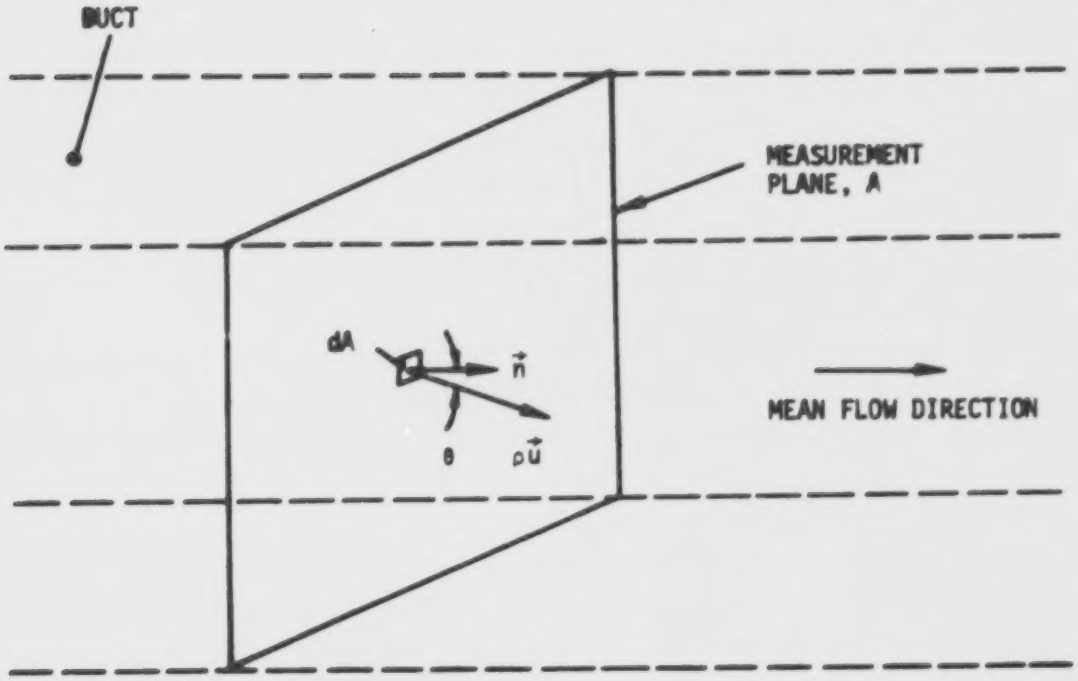
ρ = local stream density, gm/cm^3

$\vec{u}$ = local velocity vector, m/sec

$\vec{n}$ = unit vector normal to measurement plane, dimensionless

A = area of measurement plane, m^2

In order to transform this equation into a usable engineering formula, the following qualification is being applied: the local density, ρ, is taken to be that of the gaseous stream constituents only. The qualification means that liquid and solid particles entrained in the stream are not being considered, so that the flowrate, $\dot{m}$, is the total gas flowrate. The qualification is being made since the instruments to be used for this



At any point in the plane, the velocity vector $\vec{u}$ will be at an angle θ with respect to the plane's unit normal $\vec{n}$, so that the mass flow $\dot{m}$ through the plane at a point with infinitesimal area dA is given by

$$d\dot{m} = (\rho\vec{u} \cdot \vec{n})dA$$

which is then integrated over the entire plane to give

$$\dot{m} = \iint_A \rho\vec{u} \cdot \vec{n}\, dA$$

Figure 1. Flow measurement plane

application respond to the gaseous stream constituents and not the liquid and solid particles. It also permits use of the perfect gas law and Bernoulli's incompressible flow relation.

We may now begin the transformation of equation 1 into a form containing measurable parameters. From the definition of the scalar product of two vectors, we have

$$\vec{u} \cdot \vec{n} = U \cos \theta \tag{2}$$

where

$U = |\vec{u}|$, the magnitude of the velocity vector, m/sec

θ = angle between $\vec{u}$ and $\vec{n}$ (see Figure 1)

From Bernoulli's incompressible equation (Reference 4), we have

$$p_0 = p_\infty + (1/2)\rho U^2 \tag{3}$$

where

p_0 = local stream stagnation pressure, torr

p_∞ = local stream static pressure, torr

so that

$$U = \sqrt{\frac{2(p_0 - p_\infty)}{\rho}} \tag{4}$$

and

$$\vec{u} \cdot \vec{n} = (\cos \theta)\sqrt{\frac{2(p_0 - p_\infty)}{\rho}} = u \tag{5}$$

where

$u = U \cos \theta$ = velocity component normal to measurement plane, m/sec

From the perfect gas law (Reference 5), we have

$$\rho = \frac{p_\infty M}{R T_\infty} \tag{6}$$

where

M = local average molecular weight, $\frac{gm}{mole}$

R = universal gas constant, 8314.32 $\frac{gm\ m^2}{mole\ sec^2\ °K}$

T_∞ = local static temperature, °K

Substituting into equation 1, we get

$$\dot{m} = \iint_A (\cos\theta) \sqrt{\frac{2(p_o - p_\infty) p_\infty M}{RT_\infty}}\ dA \tag{7}$$

Similarly, for individual gas species flowrate we have

$$\dot{m}_i = \iint_A \mu_i M_i (\cos\theta) \sqrt{\frac{2(p_o - p_\infty) p_\infty}{MRT_\infty}}\ dA \tag{8}$$

where

$( )_i$ = property relative to gas species i

$\dot{m}_i$ = mass flow rate of species i, gm/sec

μ_i = local mole fraction of species i, $\frac{\text{moles of i}}{\text{mole}}$

M_i = molecular weight of species i, $\frac{\text{gms of i}}{\text{mole of i}}$

also

$$M = \sum_{i=1}^{I} \mu_i M_i \tag{9}$$

where

I = total number of gas species in the stream

Equations 7 and 8 represent total and individual species gas flowrate through the measurement plane, using standard measurable parameters.

2.2 CONSERVATION OF MASS-ENGINEERING REPRESENTATION

In some flow systems, the total mass flowrate can be measured directly, as in the case of a water system which empties into a tank so that the

water accumulated over a specified time period can be weighed. The following approximations apply to point measurements in process streams where measurements which involve processing the total flow are impractical for reasons of duct size or geometry. In this situation, the integrations specified in the above equations are approximated by a summation of point measurements, as given below for equations 7 and 8:

$$\dot{m} \approx \sum_{n=1}^{N} (\cos \theta_n) \sqrt{\frac{2[(p_o)_n - (p_\infty)_n](p_\infty)_n M_n}{R(T_\infty)_n}} \Delta A_n \qquad (10)$$

and

$$\dot{m}_i \approx \sum_{n=1}^{N} (\mu_i)_n M_i (\cos \theta_n) \sqrt{\frac{2[(p_o)_n - (p_\infty)_n](p_\infty)_n}{M_n R(T_\infty)_n}} \Delta A_n \qquad (11)$$

where

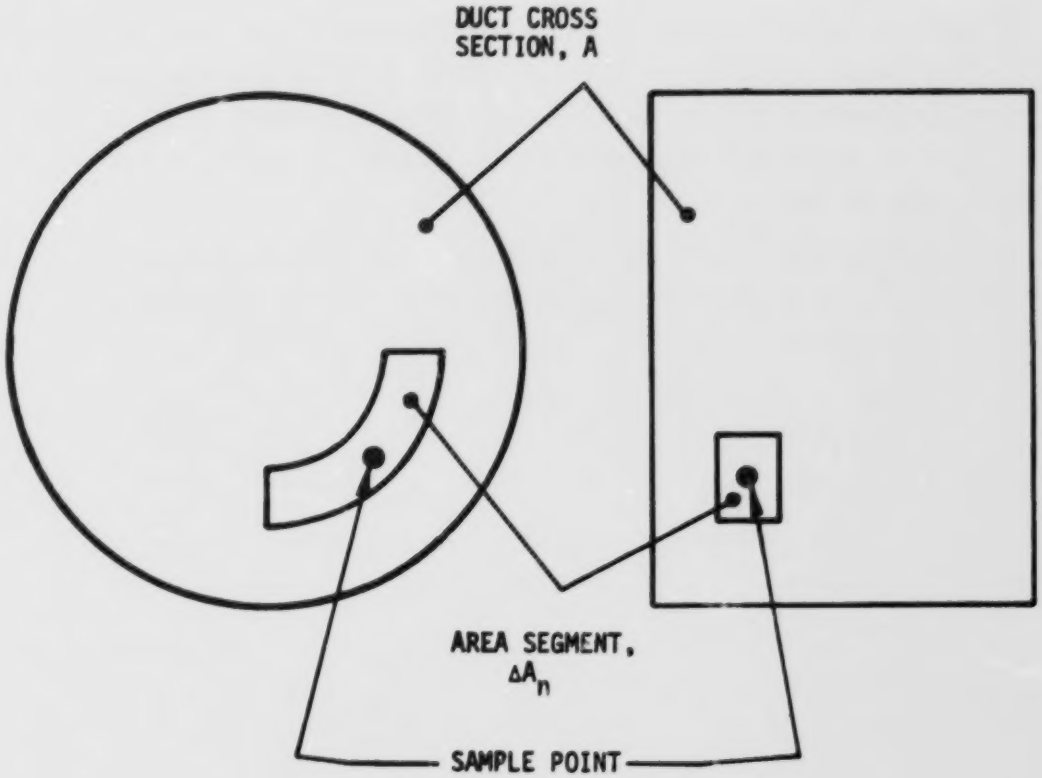
$( )_n$ = mean value of the parameter in the area segment ΔA_n

ΔA_n = area segment of control plane, m^2

N = total number of area segments

This representation is illustrated in Figure 2.

For an ideal case, the number of area segments, N, would be very large, and each of the flow parameters would be measured at each sampling point. In practice, this is usually not found to be feasible, and further simplifying assumptions are made. In standard techniques such as the EPA Federal Register methods (Reference 6), the simplifications deal with the number of sampling points, which affects N and ΔA_n, and with the variation of flow parameters such as $(p_\infty)_n$ and M_n, where simplification is achieved by assuming a constant value in the measurement plane for the parameter. Another type of assumption which can be made deals with flow proportionality. The form of equation 11 dictates that the product of the velocity and species mole fraction be computed at each point and then averaged to produce $\dot{m}_i$. In practice the technique of obtaining a gas sample at a rate proportional to the local velocity is termed flow proportional gas sampling, and is analogous to isokinetic sampling for particulate material. The most common alternate form of gas sampling is spatial gas sampling, in which samples from different area segments are considered equally, and



PARAMETER TO BE MEASURED: X

DESIRED RESULT: $\bar{X}$ N

RELATION USED: $\bar{X}A = \sum_{n=1} X_n \Delta A_n$

ACCURATE RESULTS ARE OBTAINED WHEN EACH X_n IS REPRESENTATIVE OF THE AVERAGE VALUE OF X IN AREA SEGMENT ΔA_n. GOOD ACCURACY IS ACHIEVED WHEN ΔA_n IS SMALL (LARGE N) AND/OR THE SAMPLE POINT LOCATION IN EACH SEGMENT IS CHOSEN TO GIVE THE CORRECT VALUE OF X_n.

Figure 2. Summation of area segment approximation to flow equations

the average concentration is the arithmetic mean of the individual concentrations without regard for velocity effects. There are significant simplifications which can be made to measurement systems if spatial gas sampling is acceptable from an accuracy standpoint, so the assumption is worth considering.

To represent spatial and flow proportional average concentrations or mole fractions, we must first consider the concept of velocity at standard conditions, given as

$$u_s = \frac{\rho}{\rho_s} u \tag{12}$$

where

$( )_s$ = value of parameter at standard conditions, defined to be $T_\infty = T_s = 293.16°K$ and $p_\infty = p_s = 760$ torr

Mathematically, flow proportional and spatial average mole fractions may then be defined as follows:

$$\mu_{i_{FP}} = \frac{\sum_{n=1}^{N} (\mu_i)_n u_{s_n} \Delta A_n}{\sum_{n=1}^{N} u_{s_n} \Delta A_n} = \frac{\overline{\mu_i u_s}}{\overline{u}_s} \tag{13}$$

and

$$\bar{\mu}_i = \frac{1}{A} \sum_{n=1}^{N} (\mu_i)_n \Delta A_n \tag{14}$$

where

$\mu_{i_{FP}}$ = flow proportional average mole fraction, $\frac{\text{moles of i}}{\text{mole}}$

$\bar{\mu}_i$ = spatial average mole fraction, $\frac{\text{moles of i}}{\text{mole}}$

$(\bar{\ })$ = average (mean) value

The average velocity at standard conditions is also used to calculate total volumetric flowrate, from

$$\dot{V}_s = \sum_{n=1}^{N} u_s \Delta A_n = \bar{u}_s A \qquad (15)$$

where

$\dot{V}_s$ = total volumetric flowrate at standard conditions

It is often desirable to calculate total volumetric flow relative to the mean actual pressure and temperature rather than at standard conditions, which is of course perfectly acceptable. Whenever volumetric flowrate of a gas is given, the pressure and temperature on which the calculation is based must be specified for the term to have meaning. Standard temperature and pressure are used throughout this manual.

A group of expressions for $\dot{m}$, $\dot{m}_i$, and $\dot{V}_s$ based on various assumptions is given in Table 1. The spatial average mole fraction, $\bar{u}_i$, is calculated from equation 14, and the flow proportional average mole fraction, $\mu_{i_{FP}}$, can be calculated from equation 13 or from

$$\mu_{i_{FP}} = \frac{\dot{m}_i M}{\dot{m} M_i} \qquad (16)$$

The remainder of the manual deals with the evaluation of these equations from the standpoint of accuracy, methodology, and hardware.

Table 1. PROCESS STREAM FLOW MEASUREMENT AND GAS SAMPLING EQUATIONS

Equation Number	Assumptions	Applications	Total Gas Mass Flowrate, $\dot{m}$, gm/sec
17a,b,c	None	Rigorous sampling - each parameter measured at each sampling point	$\frac{A}{n\sqrt{R}}\sum_{n=1}^{n}(\cos\theta_n)\sqrt{\frac{2(\Delta p_n)(p_s)_n M_n}{(T_s)_n}}$
18a,b1,c	Constant P_s, uncoupling of average molecular weight from velocity	TRW field test reference traverse equations	$\frac{A}{n^2}\sqrt{\frac{p_s}{R}}\left[\sum_{n=1}^{n}\sqrt{M_n}\right]\sum_{n=1}^{n}(\cos\theta_n)\sqrt{\frac{2(\Delta p_n)}{(T_s)_n}}$
18b2	Same, plus uncoupling of mole fractions from velocity		
19a,b,c	$\theta = 0$, constant P_s and M, uncoupling of temperature from velocity	EPA Federal Register methods	$\frac{A}{n^2}\sqrt{\frac{p_s M}{T}}\left[\sum_{n=1}^{n}\sqrt{\frac{1}{(T_s)_n}}\right]\sum_{n=1}^{n}\sqrt{2(\Delta p_n)}$
20a1,b1,c1	Constant P_s, uncoupling of average molecular weight from velocity, averaging M_n before taking square root, uncoupling of mole fraction from velocity in 20b1	TRW recommended equations for continuous monitoring: a1,b1 and c1 assume point velocity sensor array, a2,b2 and c2 assume use of Annubar as velocity sensor. All equations assume a point gas sampling array, K = calibration factor. Ideally $K \gtrsim 1$.	$K\frac{A}{8^2}\sqrt{\frac{p_s}{R}}\left[\sqrt{\sum_{n=1}^{8}M_n}\right]\sum_{n=1}^{8}(\cos\theta_n)\sqrt{\frac{2(\Delta p_n)}{(T_s)_n}}$
20a2,b2,c2	Same, plus assumes capability of Annubar to sense representative velocity		$K\frac{A}{8^{.5}}\sqrt{\frac{p_s}{R}}(\cos\theta)\sqrt{\frac{2\bar{\Delta p}}{T_s}}\sqrt{\sum_{n=1}^{8}M_n}$

*Equal area segments used in all cases ($\Delta A_n = \frac{A}{n}$)

Table 1 (Cont). **PROCESS STREAM FLOW MEASUREMENT AND GAS SAMPLING EQUATIONS**

Relation for Parameter to Be Calculated *	
Species Gas Mass Flowrate, $\dot{m}_i$, gm of i/sec	Total Volumetric Flowrate, $\dot{V}_s$, m^3/sec
$\frac{AM_i}{N\sqrt{R}} \sum_{n=1}^{N} (\mu_i)_n (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)(p_-)_n}{M_n (T_-)_n}}$	$\frac{AT_s\sqrt{R}}{Np_s} \sum_{n=1}^{N} (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)(p_-)_n}{M_n (T_-)_n}}$
$\frac{AM_i}{N^2} \sqrt{\frac{p_-}{R}} \left[\sum_{n=1}^{N} \sqrt{\frac{1}{M_n}}\right] \sum_{n=1}^{N} (\mu_i)_n (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)}{(T_-)_n}}$ $\frac{AM_i}{N^3} \sqrt{\frac{p_-}{R}} \left[\sum_{n=1}^{N} \sqrt{\frac{1}{M_n}}\right] \left[\sum_{n=1}^{N} (\mu_i)_n\right] \sum_{n=1}^{N} (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)}{(T_-)_n}}$	$\frac{AT_s}{N^2 p_s} \sqrt{Rp_-} \left[\sum_{n=1}^{N} \sqrt{\frac{1}{M_n}}\right] \sum_{n=1}^{N} (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)}{(T_-)_n}}$
$\frac{AM_i}{N^2} \sqrt{\frac{p_-}{RN}} \left[\sum_{n=1}^{N} \sqrt{\frac{1}{(T_-)_n}}\right] \sum_{n=1}^{N} \mu_i \sqrt{2(\Delta p_n)}$	$\frac{AT_s}{N^2 p_s} \sqrt{\frac{Rp_-}{N}} \left[\sum_{n=1}^{N} \sqrt{\frac{1}{(T_-)_n}}\right] \sum_{n=1}^{N} \sqrt{2(\Delta p_n)}$
$K \frac{AM_i}{8^{1.5}} \sqrt{\frac{p_-}{R}} \left[\sum_{n=1}^{8} M_n\right]^{-1/2} \left[\sum_{n=1}^{8} (\mu_i)_n\right] \sum_{n=1}^{8} (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)}{(T_-)_n}}$ $K \frac{AM_i}{8^{.5}} \sqrt{\frac{p_-}{R}} (\cos\theta) \sqrt{\frac{2\Delta p}{T_-}} \left[\sum_{n=1}^{N} M_n\right]^{-1/2} \left[\sum_{n=1}^{N} (\mu_i)_n\right]$	$K \frac{AT_s}{8^{.5} p_s} \sqrt{Rp_-} \left[\sum_{n=1}^{8} M_n\right]^{-1/2} \sum_{n=1}^{8} (\cos\theta_n) \sqrt{\frac{2(\Delta p_n)}{(T_-)_n}}$ $K \frac{AT_s 8^{.5}}{p_s} \sqrt{Rp_-} (\cos\theta) \sqrt{\frac{2\Delta p}{T_-}} \left[\sum_{n=1}^{8} M_n\right]^{-1/2}$

3. ERROR ANALYSIS

Three types of errors will be considered in the following discussion: random errors, systematic errors, and mistakes. Working definitions for each type of error are as follows, based on discussion in Reference 7:

- Mistake - an incorrect action, such as misplacing a decimal point when writing down data.
- Systematic error - a reproducible error such as a shift in output of an electronic device due to ambient temperature changes
- Random error - a nonreproducible error which may usually be described by a normal error distribution; the error associated with an accurately calibrated instrument is a measure of the instrument's random error.

It is not always clear which category a particular error belongs in. If an instrument operator makes an error in reading a dial because of parallax, it may be a mistake. If he continually makes the same error, say by always having his head in the same position and always looking through his right eye, the error may become systematic. If he moves his head around randomly and takes readings with either and/or both eyes, the error may be termed random. For purposes of this report, it is being assumed that mistakes are due to test personnel carelessness, systematic errors are due to physical effects, either known or unknown, and random errors are unavoidable errors which are due to the limitations of the systems being used.

Since mistakes and systematic errors can be either eliminated or reduced to a minimum through the application of proper test procedures, estimates of the random error associated with a particular system give the best indication of achievable system accuracy. A system error analysis performed as a preliminary task prior to installation of a continuous monitoring system can help to assure optimum system accuracy by pointing out

the largest error sources, which then allows for proper allocation of money and manpower to the most critical system areas.

The following example is presented to illustrate error terminology to be used in the remainder of the manual. Consider a typical pressure measurement where the true and measured values are:

True pressure: 500 Torr
Measured pressure: 600 $\pm$ 6 Torr

The systematic error for the measurement would be 100 Torr, or 20% of the true value. The random error, which is identical to the uncertainty of the measurement, would be 6 Torr, or 1% of the measured value. If we now calibrate the pressure instrument to eliminate the systematic error, we will have

Corrected pressure: 500 $\pm$ 5 Torr.

The systematic error is now zero, which it should be for a properly calibrated instrument, while the random error, or uncertainty, remains at $\pm$ 1% of the reading. We may now say that the pressure measurement device has an accuracy of $\pm$ 1%, which means that the random error, or uncertainty, in the measurement is $\pm$ 1%. In the remainder of the manual, the terms "accuracy," "random error," and "uncertainty" are used interchangeably, while "systematic error" and "mistake" are not used interchangeably with any other terms. Following is a random error analysis of the equations derived in Section 2. It in turn is followed by a brief discussion of systematic errors and mistakes.

3.1 SYSTEM RANDOM ERRORS

3.1.1 Single Point Measurement Accuracies

The following technique is taken from Reference 7, "The Analysis of Physical Measurements," Chapter 11. Assume that it is desired to calculate parameter G, which is a known function of variables H_1, H_2, . . . H_r, given by

$$G = f(H_1, H_2, \ldots, H_r) \tag{21}$$

where f denotes the functional relationship. Define the error in the measurement of variable H_r as e_r. The standard deviation of the measurement of M_r is then given by

$$\sigma_r^2 = \lim_{N\to\infty} \frac{\sum_{n=1}^{N} e_r^2}{N} \tag{22}$$

where

σ_r = standard deviation of H_r

N = number of measurements

By derivation, the standard deviation of G is then given as

$$\sigma_G^2 = \left(\frac{\partial f}{\partial H_1}\sigma_1\right)^2 \cdot \left(\frac{\partial f}{\partial H_2}\sigma_2\right)^2 + \text{----} + \left(\frac{\partial f}{\partial H_r}\sigma_r\right)^2 \tag{23}$$

For purposes of the present discussion, it is most convenient to analyze equations 17-20 in terms of single point measurement accuracies, and then to make a determination of the effects of number and location of sampling points. Thus the following single point equations will be considered first:

$$\dot{m} = A(\cos\theta)\sqrt{\frac{2(\Delta p)p_\infty M}{RT_\infty}} \tag{24}$$

$$\dot{m}_i = AM_i\mu_i(\cos\theta)\sqrt{\frac{2(\Delta p)p_\infty}{RMT_\infty}} \tag{25}$$

$$\dot{V}_i = A\frac{T_s}{p_s}(\cos\theta)\sqrt{\frac{2(\Delta p)p_\infty R}{MT_\infty}} \tag{26}$$

$$M = \sum_{i=1}^{I} M_i\mu_i \tag{27}$$

These equations, when subjected to the above analysis, result in the following equations in the form of equation 23:

$$\frac{\sigma_{\dot{m}}^2}{\dot{m}^2} = \frac{\sigma_{\dot{V}_s}^2}{\dot{V}_s^2} = (\tan^2\theta)\sigma_\theta^2 + \frac{\sigma_A^2}{A^2}$$

$$+ (1/4)\left(\frac{\sigma_{\Delta p}^2}{\Delta p^2} + \frac{\sigma_{p_\infty}^2}{p_\infty^2} + \frac{\sigma_M^2}{2} + \frac{\sigma_{T_\infty}^2}{T_\infty^2}\right) \qquad (28)$$

This means that the uncertainty is the same for $\dot{m}$ as for $\dot{V}_s$. For the other parameters, we have

$$\frac{\sigma_{\dot{m}_i}^2}{\dot{m}_i^2} = \frac{\sigma_{\dot{m}}^2}{\dot{m}^2} + \frac{\sigma_{\mu_1}^2}{\mu_1^2} \qquad (29)$$

$$\frac{\sigma_M^2}{M^2} = \sum_{i=1}^{I} \frac{M_i^2}{M} \sigma_i^2 \qquad (30)$$

The standard deviation, σ, is a measure of the uncertainty in the accuracy of the associated parameter. For the case of a normal error distribution, there is a 68.3% probability that the error associated with a single measurement will be less than $\pm\sigma$, and a 95.5% probability that the error will be less than $\pm 2\sigma$. The $\pm 2\sigma$ band is normally used for most engineering applications, so that if an instrument is said to have an accuracy of $\pm 2\%$, it means that $2\sigma = 2\%$ or $\sigma = 1\%$. Equations 28 and 29 are given in a form which allows for convenient discussion in terms of accuracy expressed as percent of reading.

The θ term in Equation 28 may be confusing at first glance, since $\tan^2\theta$ becomes infinite at $\theta = 90°$. The explanation is as follows: as θ approaches 90°, $\dot{m}$ approaches zero and $\tan^2\theta$ approaches infinity, which makes both sides of the equation approach infinity. However, the problem disappears if we multiply through by $\dot{m}^2$ (or $\dot{V}_s^2$ for that form) and then

substitute for $\dot{m}$ (or $\dot{V}_s$) from equation 24 (or 26), as all terms become finite. The special case of $\theta = 90°$ is discussed in more detail in Section 5, along with a discussion of alignment errors in general. For the purposes of this section, it is adequate to note that in general for a well designed probe, empirical data show that

$$|(\tan \theta)\sigma_\theta| \leq .025 \tag{31}$$

The following may be concluded from the form of equations 28 and 29:

- The uncertainty in the determination of total gas mass flow is the same as for total gas volumetric flow.
- The uncertainty in the measurement of species mass flow rate cannot be less than that for total mass flow rate.
- A given percentage uncertainty in cross-sectional area results in a larger system uncertainty than would the same percentage uncertainty in pressure, temperature, or average molecular weight.

The first two are self explanatory; the third is mentioned because in many cases, very little attention is devoted to obtaining a good measurement of cross-sectional area.

Nominal achievable accuracies for each of the parameters in equations 28 and 29 are given in Table 2:

Table 2. NOMINAL UNCERTAINTIES FOR MEASURED PARAMETERS AT A SINGLE POINT

Parameter	Achievable Uncertainty, Percent	
	σ	2σ
P_∞	1	2
Δp	2	4
T_∞	.5	1
M	1	2
A	1	2
μ_i	1	2

Substituting these values into equations 28 and 29 gives, using .025 for $(\tan\theta)\sigma_\theta$, we obtain

$$\frac{\sigma_{\dot{m}}}{\dot{m}} = \frac{\sigma_{\dot{V}_s}}{\dot{V}_s} = 3.0\% \tag{32}$$

and

$$\frac{\sigma_{\dot{m}_f}}{\dot{m}_f} = 3.1\% \tag{33}$$

which corresponds to 2σ uncertainties on the order of $\pm 6\%$ for each of the three parameters.

The nominal accuracies given in Table 2 are discussed further in Section 5. The key results of this section are equations 28 and 29, which show the relationships among the various parameters involved in terms of accuracy. Also, the nominal achievable single point accuracy of $\pm 6\%$ becomes a reference point to which other error sources can be compared. Following is a discussion of multiple point sampling errors.

3.1.2 Multiple Point Measurement Accuracies

Single point measurements can be represented by exact equations, which makes them directly amenable to a standard error analysis as was performed above. Multiple point measurement equations are not exact (e.g. a summation is used instead of an integration) and also involve simplifying assumptions. For present purposes, we can represent the total system random error as follows:

$$\sigma_{SE}^2 = \sigma_{SPE}^2 + \sigma_{AE}^2 + \sigma_{ME}^2 + \sigma_{TE}^2 \tag{34}$$

where

σ_{SE} = total system uncertainty, percent

σ_{SPE} = single point measurement uncertainty, percent

σ_{AE} = assumption uncertainty, percent

σ_{ME} = mapping uncertainty, percent

σ_{TE} = temporal uncertainty, percent

The single point measurement uncertainty was treated above, resulting in $\sigma_{SPE} \approx$ 3% for a nominal achievable case. Assumption uncertainties are due to mathematical simplifications such the assumption of constant static pressure and average molecular weight in the measurement plane. Mapping uncertainties deal with the number and location of measurement points. Temporal uncertainties occur when there is a significant time interval between measurements which could allow conditions to change in the measurement plane. Each of the latter three error sources is considered below.

The following discussion is based on empirical data obtained from several coal fired power plants, and may be expected to apply in general to process streams with the following characteristics:

- Cross-sectional shape: round or rectangular
- Stream static pressure: local atmospheric pressure $\pm$10%
- Bulk composition: air, combustion products and water vapor
- Flow velocity: $\leq$ 30m/sec.

3.1.2.1 Evaluation of Assumptions

This section deals with the equations in Table 1. In that table, equations 17 are presented for reference as the most rigorous form which involves no simplifying assumptions. Equations 18-20 involve various assumptions concerning stratification of and interaction among the parameters. The following evaluation makes use of the data base from References 1 and 2 along with a general knowledge of process streams to determine the effects of the assumptions on system accuracy.

3.1.2.1 Stratification/Interaction Considerations

Static pressure, p_s: of the variables in equation 17, static pressure will vary the least across the sampling plane. The static pressure

variation will rarely be greater than $\pm$0.2% of the mean value unless there is a large leak to or from the atmosphere at the sample plane location. Thus the assumption of constant pressure in equations 18-20 helps to simplify instrumentation and data reduction without compromising system accuracy.

Static Temperature, T_s: Temperature stratification itself has not been examined as much as have velocity and compositional stratification. However, it can be intuitively recommended that temperature be measured at every point where velocity is measured, and the data reduction performed in the "coupled" sense of equation 17 rather than the "uncoupled" manner of equation 19. Since the stream velocity must go to zero at the wall of the duct and most processes take place at higher than ambient temperature, it is to be expected that both velocity and temperature will be at a minimum near the wall, and at a maximum away from the wall. Since both parameters vary in the same manner, they may be said to be coupled, and so should be treated that way in the data reduction scheme. In a practical sense, temperature is perhaps the easiest parameter to measure, so taking simultaneous velocity (Δp) and temperature measurements does not present a problem. Since there is no significant "cost" involved in handling the temperature data in the rigorous form, the temperature should be handled as in equation 17 and 18 rather than in the uncoupled manner of equation 19.

Average Molecular Weight, M: In combustion streams, the predominant gaseous components are N_2, CO_2 and CO, O_2, and H_2O. EPA Federal Register Methods 2, 3 and 4 rely upon the validity of this assumption, and the assumption is supported by data in Reference 8 for fossil fuel power plants, municipal incinerators, and a number of industrial processes. It is also the case that most of these streams involve the use of excess air. In most of these streams, then, the gas will be composed of 70-80% N_2, which strongly limits the variation which will be observed in M. During a typical TRW field test, for a 49 point traverse the maximum deviation from the mean for M was $\pm$1%, although for the same traverse, individual gas species concentrations differed by as much as $\pm$25% from the mean concentration. Since the available data, as discussed below, indicate that it

is acceptable to decouple the measurement of local concentration (mole fraction) from velocity, it would certainly be appropriate then to decouple average molecular weight from velocity. In addition, the low observed stratification of M lends support to the single point determination of M in equation 19.

Mole Fraction (concentration), μ_i: In Reference 2, twenty six manual traverses were analyzed to determine the extent of coupling between concentration and velocity. Fourteen of the traverses were conducted by TRW personnel, eight were obtained from Exxon Research, and four from a report by Walden Research (Reference 9). The average species concentrations were calculated using the coupled (flow proportional) method of equation 19b1 and using the uncoupled method of equation 19b2. For the 26 runs, the average difference between the two calculations was .83%, and the worst case difference was 3.7%, despite the fact that the average gas stratification level (discussed and defined in Section 4) was $\pm$15%. This led to the conclusion that spatial gas sampling is acceptable, and will not result in a significant increase in system random error. This conclusion has very strong hardware and methodology implications for continuous monitoring systems, as discussed in Sections 4 and 5.

3.1.2.2 Mapping Errors

This section applies to manual traverses. Number and location of sampling points for continuous monitoring are discussed at length in Section 4. As a general statement, it can be said that the number of sampling points should be maximized to obtain the best accuracy (minimum σ_{ME}). This statement must be tempered by the labor costs involved in taking data at a large number of points, and by the fact that the traverse should be performed over a short period of time to minimize the effect of temporal flow variations. A more practical approach is to select the minimum number of points which can be used without sacrificing accuracy.

A computer analysis has been performed on the 26 runs mentioned above to determine the effect of varying the number of sampling points. All runs were performed in rectangular ducts. In addition, eighteen velocity traverses were also considered. For each of the traverses, the test data

were input to a program which could compute local velocity or concentration at any point using curve fitting techniques. Average flowrate or concentration was then computed for n x n centroid of equal area arrays where $1 \leq n \leq 7$. Results were then compared to that obtained from a 25 x 21 array (i.e. 525 points) and normalized with respect to the single point error. The final result is shown in Figure 3. No notable increase in accuracy was noted for arrays using in excess of sixteen points. This result is considered significant for the practical reason that gas traverses tend to be very time consuming. In testing at a coal fired power plant, TRW personnel routinely performed 49 point (7 x 7 array) velocity traverses using a standard pitot-static probe in less than an hour, while the corresponding 49 point gas traverses took up to 8 hours, largely due to the cycle time of the gas chromatographs used.

For the 26 gas sample traverses and 18 velocity traverses analyzed to produce Figure 3, the average concentration error for a 16 point traverse was 1.1%, and the average velocity error for a 16 point traverse was 1.4%. This means that for the measurements of interest, we may expect σ_{ME} to be less than 2% when 16 point manual traverses are used.

3.1.2.3 Temporal Variations

Changes in velocity or concentration during the course of the measurements can pose a problem for manual traverses. The obvious guiding rules are to complete the traverse as rapidly as possible, and to perform the traverse during a steady period in the operating cycle. It is usually a fact of life that the variations which occur must simply be lived with, so the best way to minimize them is through the use of fast response equipment, which minimizes the time spent at any one measurement point, and to minimize the number of measurement points. An absence of temporal variations will usually appear as consistent results from two or more consecutive traverses, and this type of repeatability work is the best way to check for the existence of temporal variations.

3.1.2.4 Continuous Monitoring System Considerations

Continuous measurement systems pose a special accuracy problem. They can be designed to operate under assumptions similar to those for manual measurements so that σ_{AE} can be kept small, and will have a fast time

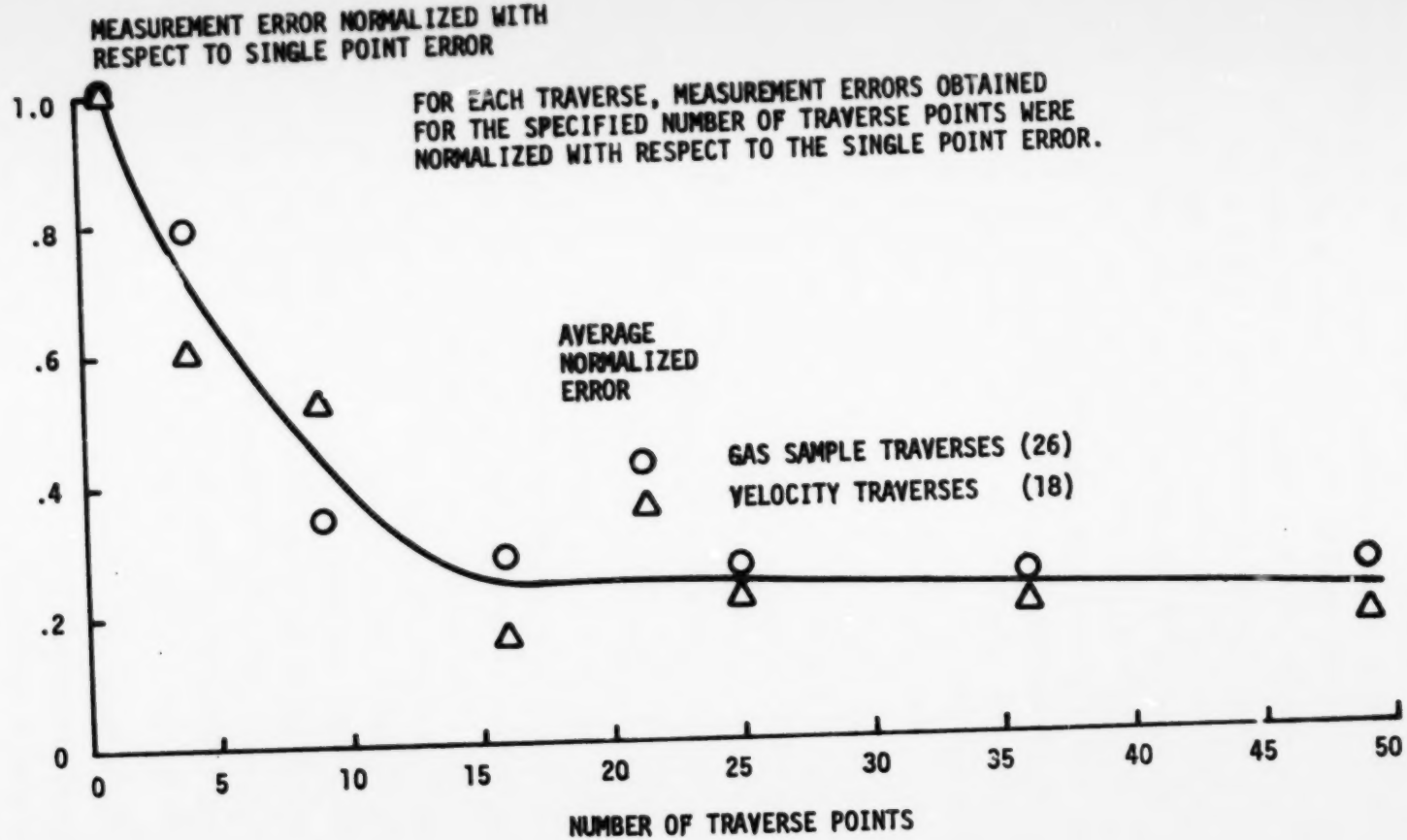


Figure 3. Normalized measurement error versus number of sampling points for volumetric flow and gas sample traverses

response so that σ_{TE} will be negligible. The problem is that the cost of a continuous system which used as many measurement points as a manual traverse would be prohibitive. Use of as few as one measurement point can result in very large mapping uncertainties, σ_{ME}, which often become the largest contribution to total system error. The recommended relations given in Table 1 for continuous monitoring systems (Equation 20), are based on the use of a single gas sampling probe containing eight ports, and as few as one velocity sensor. These are described in Section 5. Such a system has been successfully demonstrated in the field as described in References 1 and 2. For manual measurements, it is certainly reasonable to use enough measurement points so that the mapping uncertainty σ_{ME} is small compared to the single point uncertainty σ_{SPE}. For continuous systems, keeping σ_{ME} about the same as σ_{SPE} represents a reasonable tradeoff between accuracy and cost.

3.2 SYSTEMATIC ERRORS AND MISTAKES

Systematic errors are most likely to occur as instrument calibration shifts, inaccurate calibration gases, and other quality assurance related phenomena. Like mistakes, they must be minimized through precise, correct test procedures and proper training of personnel. One of the most difficult to control systematic error sources is the calculation of the duct cross sectional area, A. As shown in equation 28, uncertainty in the cross sectional area has a relatively strong effect on system accuracy, but ordinarily less effort is devoted to this parameter than to any other. This is usually due to the inability of the test crew to measure A directly, so that it must be determined from blueprints. It is definitely recommended that the cross-sectional area of a designated test section be physically measured in new sources after construction is completed, and estimates made concerning how the area may change during actual operation due to temperature and pressure effects. The same procedure should be performed if possible at existing sites during a non-operating period, which would also allow assessment of the effects of scale build up on the walls. It is not difficult to imagine the actual cross-sectional area of a duct differing by 5% from the value indicated by a blueprint. Such an error would have a very adverse effect on the accuracy of emission measurements taken at that location.

Discussion of specific technique details which tend to result in systematic errors or mistakes when not performed properly is given in Section 4.

3.3 SUMMARY

The error analysis results are summarized in terms of achievable 2σ uncertainties (random errors) in Table 3.

Table 3. NOMINAL UNCERTAINTIES FOR PROCESS STREAM MEASUREMENT SYSTEMS

Parameter	Types of Measurement	Uncertainty, Percent				
		$2\sigma_{SE}$	$2\sigma_{SPE}$	$2\sigma_{AE}$	$2\sigma_{ME}$	$2\sigma_{TE}$
$\dot{m}$, $\dot{m}_f$, $\dot{V}_s$	Manual traverse	7	6	2	3	2
	Continuous	9	6	2	6	0
$\bar{\mu}_f$	Manual traverse	4	2	2	2	2
	Continuous	5	2	2	4	0

The above figures apply in general to process stream measurement systems utilizing good quality available hardware and proper procedures. In order to get an idea of the achievable accuracy for a proposed measurement system, equation 28 (or an appropriate variation thereof which is correct for the proposed instruments) should be used to calculate the single point accuracy, as was done to calculate the above nominal figures. If proper methodology is applied and care taken to avoid systematic errors, system accuracies approaching the calculated value should be achievable in the actual application. The following sections deal with methodology and instrumentation to achieve optimum system accuracies.

4. SAMPLING METHODOLOGY

This section deals with site selection, probe placement, and other procedural details involved in flow and composition measurement in stationary source process streams. Since procedures for manual traverses are well established, most of the section deals with methodology for continuous monitoring systems. In all cases, the objective is to provide optimum accuracy at minimum cost. Specific hardware items are discussed as required; details of hardware selection and evaluation are presented in Section 5. It is assumed throughout the section that the parameters to be determined are total gas mass flow, $\dot{m}$, species mass flow, $\dot{m}_i$, total volumetric flow, $\dot{V}_s$, and/or average mole fraction (concentration), $\bar{\mu}_i$.

4.1 MANUAL SAMPLING

4.1.1 Site Selection

Very often, site selection is beyond the control of the sampling team — testing must be performed using existing sample ports, which may or may not be ideally located. The following rules are a guide for site selection if there is a choice of locations, and are presented in order of priority:

1. Select a location which allows the greatest length (in effective duct diameters) of ducting ahead of the sample plane, allowing for 20% of the straight run to be downstream of the sample plane.
2. Select a location in a circular duct rather than in a rectangular duct unless there is a strong swirl pattern in the circular duct.
3. Avoid sampling immediately downstream of areas where significant leakage into the duct occurs, unless a purpose of testing is to determine the extent of the leakage.

These are standard suggestions for site selection, and are all subject to the common sense considerations of accessability, working conditions, etc.

Similar suggestions are given in References 8, 11, and 12. The reasoning behind these rules follows directly from the error analysis of Section 3. Rule 1 helps to insure minimum flow angularities ($\theta \neq 0$). As shown in equation 28, the error due to flow angularity is a minimum at $\theta = 0$. Since flow angularity presents a difficult instrumentation problem, as is discussed in Section 5, all efforts should be made to minimize it.

Past experience has shown that for a given number of sampling points, more accurate velocity data can be taken in a circular duct than in a rectangular duct. In addition, it is usually easier to take measurements in a circular duct since fewer sampling ports are involved. The caution to avoid swirl patterns, often intentionally produced in stacks, is based on flow angularity considerations.

Areas of leakage should be avoided to minimize both flow angularity and compositional stratification. It is intuitively obvious that a representative gas sample can best be obtained when there is minimum compositional stratification in the sampling plane.

4.1.2 Number and Distribution of Sampling Points

EPA Federal Register Method #1 (Reference 6) calls for the number of sampling points to be selected as a function of the distance from the sampling site to the nearest upstream and downstream disturbances (Figure 4), with the minimum number of points being 12. The most obvious deficiency of Method 1 is that it does not state how many points to use if the sampling site is less than two diameters downstream or less than half a diameter upstream of a disturbance. For velocity traverses, the British Standards Institute recommends the method shown in Figure 5 (taken from Reference 8), where the number of subdivisions is based solely on the cross-sectional area. The BSI method also requires additional sampling points in the subdivisions adjacent to the walls. If we take as an example a 3.05 m x 3.05 m (10 ft x 10 ft) duct, the BSI method would require a minimum of 560 sample points in 400 subdivisions, and would require about 60 sampling ports to gain access to the points.

The objective in a manual traverse is to obtain representative velocity and/or gas sampling data in each of the specified area segments, so that the summation of all data points gives a value representative of the

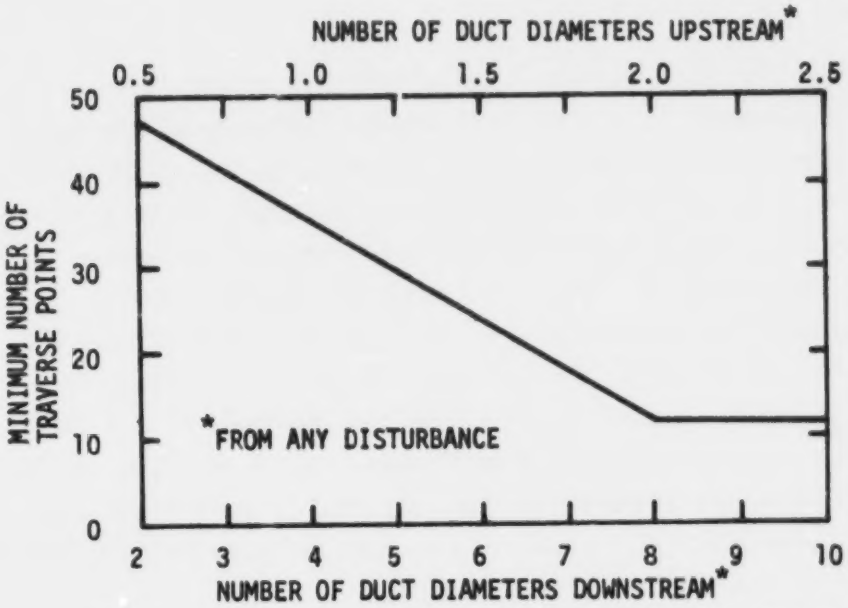


Figure 4. Minimum number of traverse points - EPA Method 1

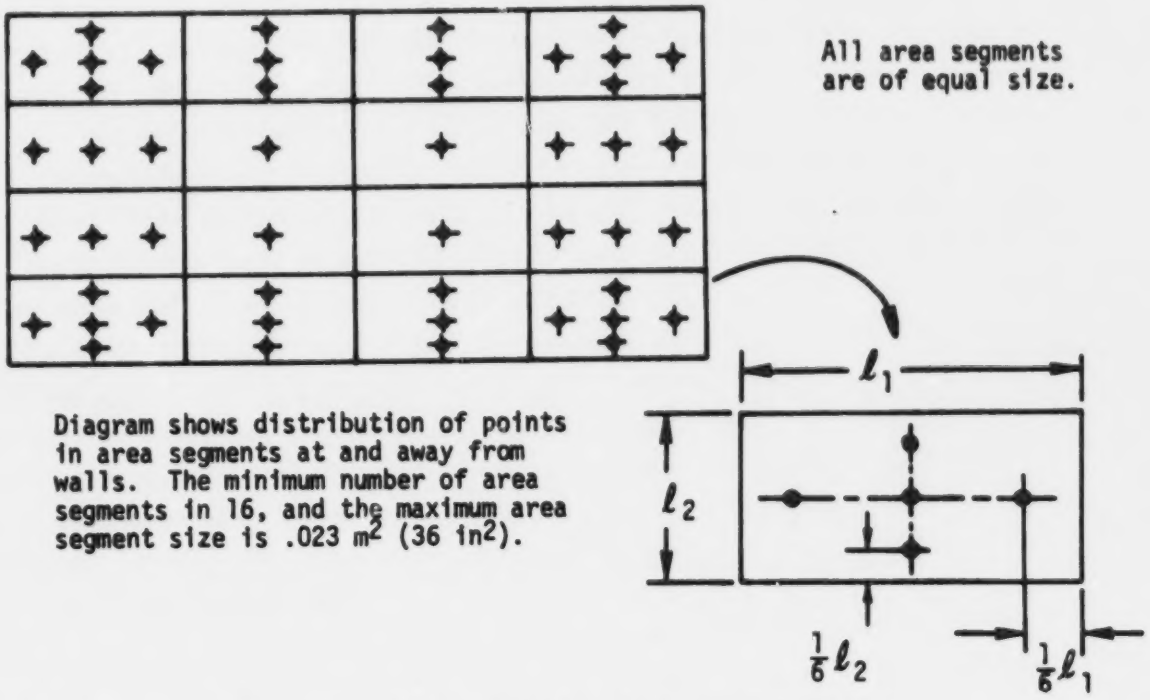
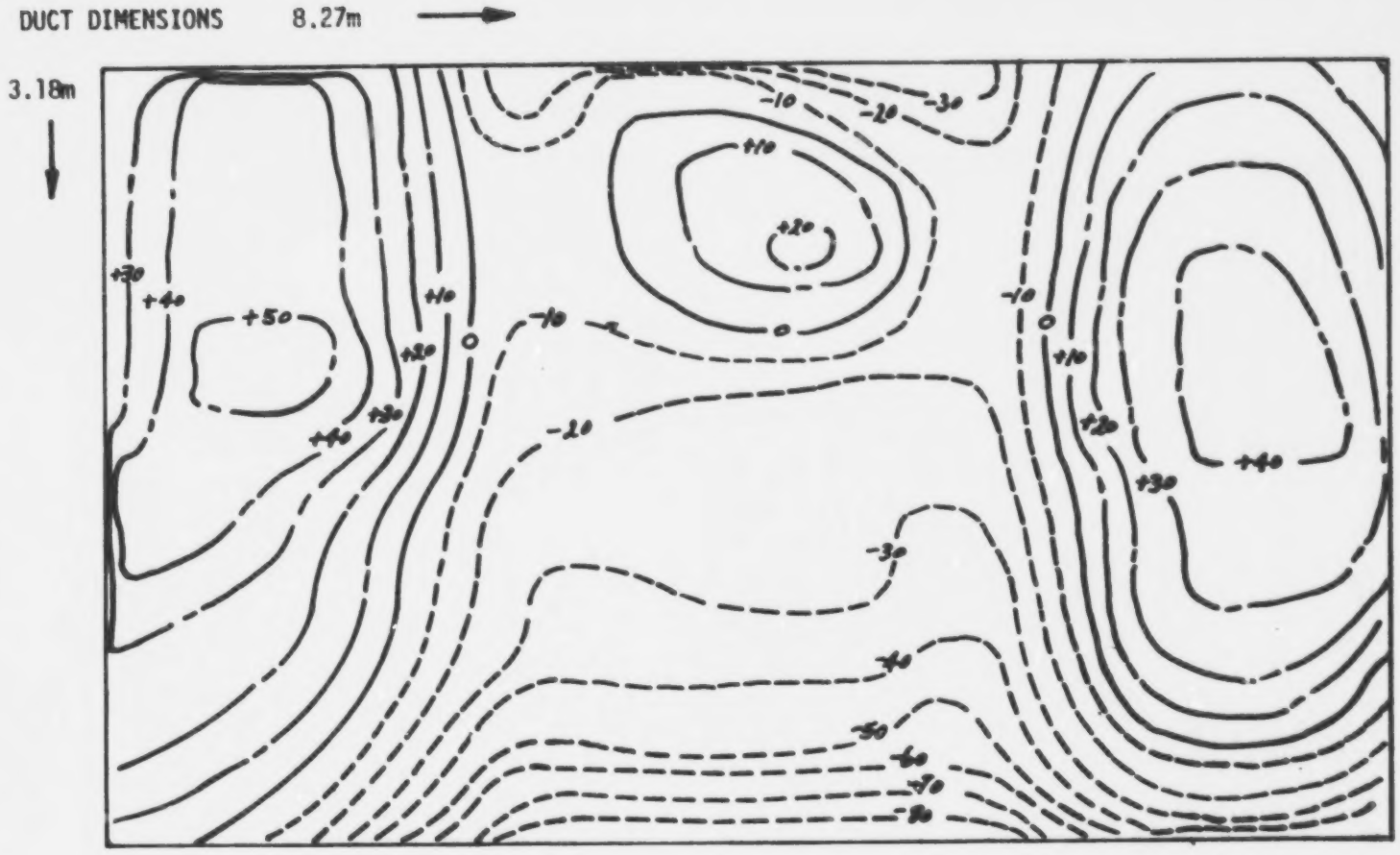


Diagram shows distribution of points in area segments at and away from walls. The minimum number of area segments in 16, and the maximum area segment size is .023 m^2 (36 in^2).

Figure 5. BSI rectangular duct mapping scheme

total flow through the cross section. The probability of obtaining a representative measurement in a given area segment increases as the variation (stratification) of the parameters to be measured in the area segment decreases. Typical normalized velocity and concentration profiles are shown in Figures 6 and 7, where the contours represent percentage deviations from the average velocity and average concentration. The computer program used to compute the profiles is described in Reference 2. The raw data were from 48 point (6 x 8) traverses performed by Exxon Research and Engineering Company under EPA contract 68-02-1722 at a TVA coal fired power plant. It is clear from Figures 6 and 7 that the smaller the area segment, the more uniform the flow pattern is within the segment. As the number of sample points increases, then, the representativeness of the measurement in each area segment also increases.

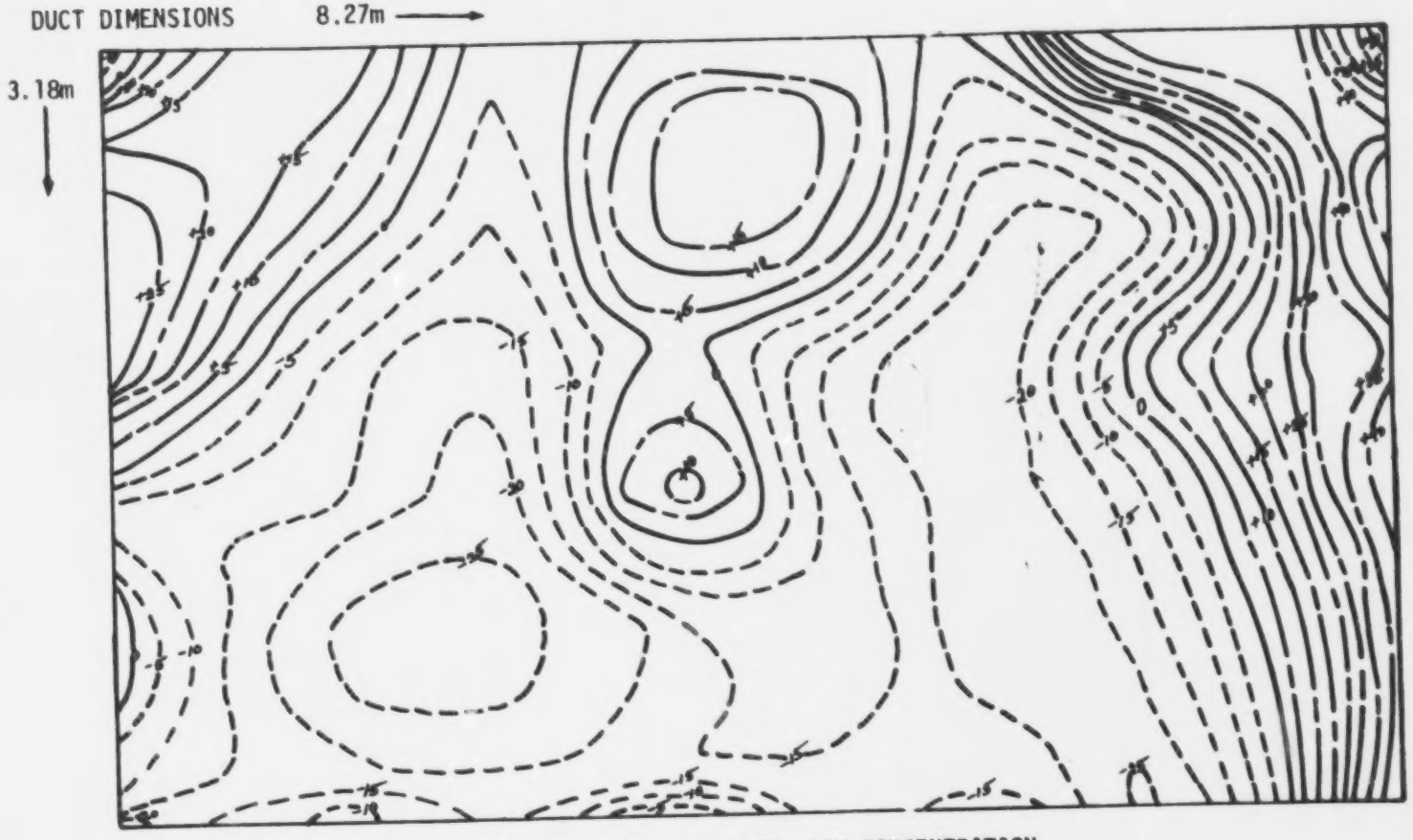
There is, however, a conflicting accuracy consideration: as the number of data points increases, the time required for the traverse also increases, which gives use to the problem of temporal flow variations. When a large number of sampling points is used, data at each point may be representative for the respective area segment at the time the measurement was performed while the total accumulated data are in error due to flow changes during the period of the traverse. The problem with temporal variations is that they are very difficult to assess in a quantitative manner, and so the usual procedure is to simply ignore them. It is our belief that better accuracy can be obtained by taking a relatively small number of points during a traverse and then repeating the traverse one or more times to check for consistency of the data than by performing a single traverse which involves a very large number of points. This belief led to the analysis which produced Figure 3, which was discussed briefly in Section 3. The 26 gas sample traverses used are considered representative, and were obtained by three completely independent testing groups. The velocity traverses were obtained under representative to worst case conditions: most of them were obtained at a location approximately 0.4 effective diameter downstream of a large disturbance and 0.1 diameters upstream from a large disturbance. The analysis performed had two major results with respect to manual sampling:



PROFILES ARE VARIATION IN 10% INCREMENTS FROM MEAN VELOCITY

MEASURED MEAN VELOCITY = 6.81 m/sec

Figure 6. Normalized velocity distribution -- Exxon run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 4.36% (DRY GAS)

Figure 7. Normalized O_2 concentration distribution--Exxon run 1

1. No significant increase in accuracy was noted for traverses involving more than 16 points.

2. For the 26 gas sample traverses and 18 velocity traverses examined, the average mapping error for μ_1 was 1.1% and for $\dot{V}_s$ was 1.8%.

The first results mean that a 16 point traverse is acceptable from a qualitative standpoint because use of a larger number of points does not represent a notable improvement; the second results mean that a 16 point traverse is acceptable from a quantitative standpoint since sampling errors of that magnitude would not seriously degrade system accuracy.

It is recognized that a sixteem point traverse is always less rigorous than the BSI method, and usually less rigorous than EPA Method 1. The 16 point traverse recommendation was arrived at after detailed examination of a sizable body of empirical data from three different sources, and the analysis is believed to be sound. In addition, the 16 point traverse must result in smaller temporal errors than traverses involving a larger number of points. It is recognized that a larger body of data must be examined before the 16 point traverse can be seriously considered as a standard technique, and we strongly encourage that such an examination be performed.

A 16 point velocity traverse can be performed in about 20 minutes; a gas sample traverse would require a somewhat longer time depending upon the type of instrumentation used. A gas sample traverse using a continuous gas analyzer or analyzers should take from 40 minutes to an hour. Sample times on this order should be acceptable for use in a large number of industrial process streams. Traverses involving more than 16 points are recommended only when it is desirable to obtain flow and concentration maps for purposes such as identification of stratification patterns. In this type of situation, traverses involving 36-64 points are recommended.

Once the number of sampling points has been selected, their location must be determined. The optimum location for velocity sampling is not necessarily the same as for gas sampling. Rectangular ducts will be considered first. There is one known fact about the velocity distribution in any duct: the velocity must be zero at the wall. In a rectangular duct, this means that the total velocity variation must be the same between each pair of walls — from zero at each wall to the maximum velocity, wherever

it occurs. This leads to the recommendation that each side of the duct should be divided into an equal number of segments for point sampling, producing an n x n sampling matrix containing n^2 sampling points, as illustrated in Figure 8a. This arrangement helps to insure minimum velocity stratification in each area segment. The velocity should be measured in the center of each segment unless there is good reason to pick a different location.

For gas sampling in rectangular ducts, the situation is different because there are no known boundary conditions for gas concentration. In this situation, the sample points should be dispersed to maximize the distance between the points. For a given number of sample points, this occurs when the area segments are as close as possible to being squares, as illustrated in Figure 8b.

It is recognized that there is not always complete freedom to select the shape of the sample array – existing sample ports must often be used out of necessity, or it may not be practical to use different array shapes for velocity and gas sampling. In such cases, array shapes should be selected according to the following criteria:

1. For an $n_1 \times n_2$ array, n_1 and n_2 should each be greater than or equal to four for a velocity traverse and not less than two for a gas sample traverse. The product $n_1 \times n_2$ should be greater than or equal to 16.

2. For a velocity traverse, it is preferable to have $n_1 = n_2$. For a gas sample traverse, it is preferable to have the ratio ℓ_2/ℓ_1 be as close as possible to one, where ℓ_2 is the length of the longer side of the area segment, and ℓ_1 is the length of the shorter side. If a single array is to be used for both velocity and gas sampling, the array should be selected according to the velocity traverse criteria.

3. All area segments should be of equal size and shape, and the sample points should be located as close as possible to the center of each segment.

For traverses in circular ducts (pipes, stacks), all common techniques involve measurements along two orthogonal diameters. The sixteen point

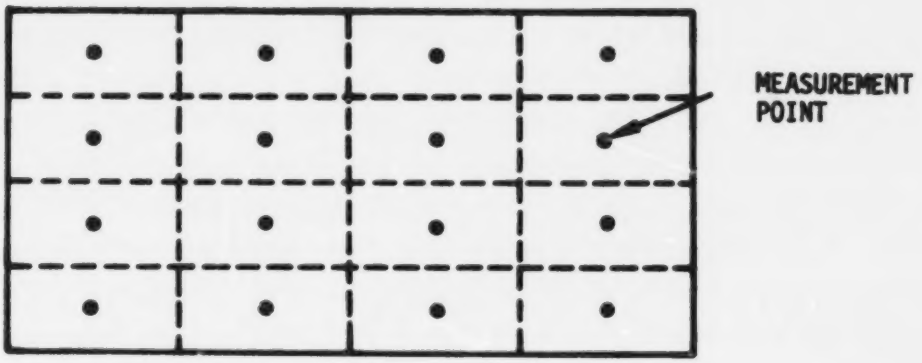


Figure 8a. Sixteen point array for manual velocity traverses

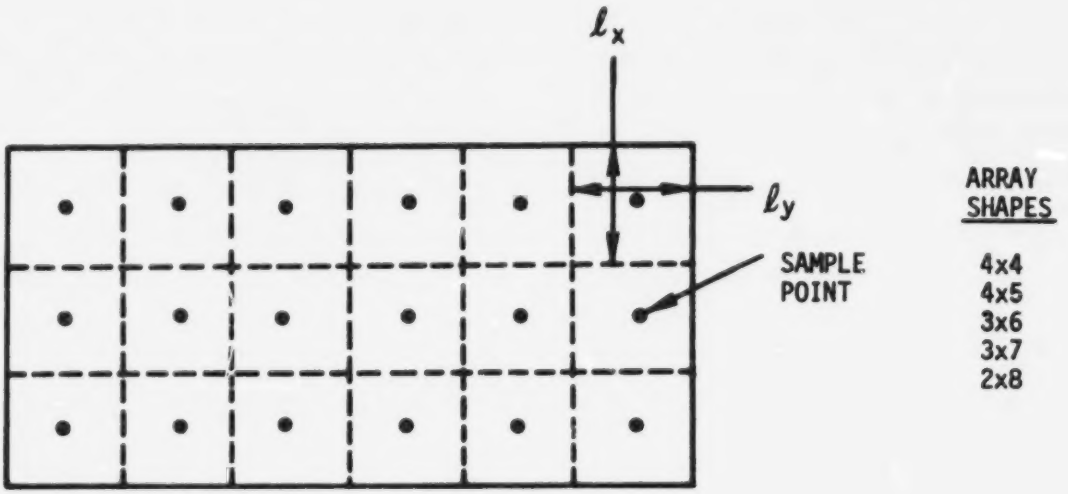


Figure 8b. Arrays for manual gas sample traverses

traverse is also recommended for use in circular ducts, although the analysis which resulted in the sixteen point recommendation involved only rectangular duct data. Past TRW experience in pilot and full scale facilities has led to the conclusion that for velocity measurement, a given number of points distributed in a circular duct will result in consistently better accuracies than the same number of points in a rectangular duct. This contention is supported by a recommendation in Reference 12 to add ducting to a rectangular duct to change it to a circular cross section if optimum accuracy is required. The conclusion is that if a sixteen point array is adequate in a rectangular duct, it will be at least as adequate in a circular one.

The tangential, or centroid of equal areas, method specified in EPA Method 1 is recommended for gas sampling in circular ducts, but not for velocity measurement. The tangential method assumes that nothing is known about the distribution of the parameter to be measured, so the sample points should be located at the centroids of the area segments. This same philosophy is used above in locating points in rectangular ducts. There is a very large body of knowledge about velocity distributions in circular ducts, and sampling methods have been developed on the basis of this knowledge which demonstrate better accuracy than the tangential method. The best of these methods appears to be the Log-Linear technique, presented in Reference 10 and also discussed at some length in References 8 and 12. The name Log-Linear is descriptive of the basic assumption used — that many velocity distributions can be closely approximated by the family of curves

$$u = c_1 + c_2 \log (y/D) + c_3 (y/D) \qquad (35)$$

where

u = velocity, cm/sec

y = distance from duct wall, cm

D = duct diameter, cm

c_1, c_2, c_3 = constants, cm/sec

The method involves dividing the duct into a number of equal area segments, and then differs from the tangential method by placing the sampling points not at the centroid of each segment, but at locations which give a representative velocity for each segment. The method has been tested extensively in TRW facilities, as described in Reference 1, and has been found very acceptable.

Sixteen point traverses are illustrated for the tangential and Log-Linear methods in Figure 9, and point locations are given in Table 4.

4.1.3 General Sampling Techniques

Procedures for manual sampling are given in Reference 3. The purpose of this section is to indicate technical details which can have a significant effect on measurement accuracies and testing efficiency. The following should be given appropriate attention:

- Measurement of Duct Cross Sectional Area - This was discussed in some detail in Section 3. In most cases, not all dimensions can be checked, and it is often necessary to rely upon blueprints. At a minimum, the dimensions from the sampling ports to the opposite wall should be physically measured and appropriate corrections made in the calculated area. These measurements must also be used to assure correct placement of the probes, since distances can differ among ports in a rectangular duct or along diameters in a circular one. Also be sure that the proper area is calculated for the instruments being used. If the duct is tapered in the region of the sample plane and an instrument such as a pitot-static probe is used to obtain velocity data, the proper area will not be the area at the sampling ports, but slightly upstream of them where the head of the probe is actually located.

- Probe Positioning and Alignment - Proper probe placement is a critical item for velocity sensors, especially in circular ducts. This requires accurate measurement of the line or diameter along which the probe must be located, as well as the height of the sampling port and connective fittings, etc.

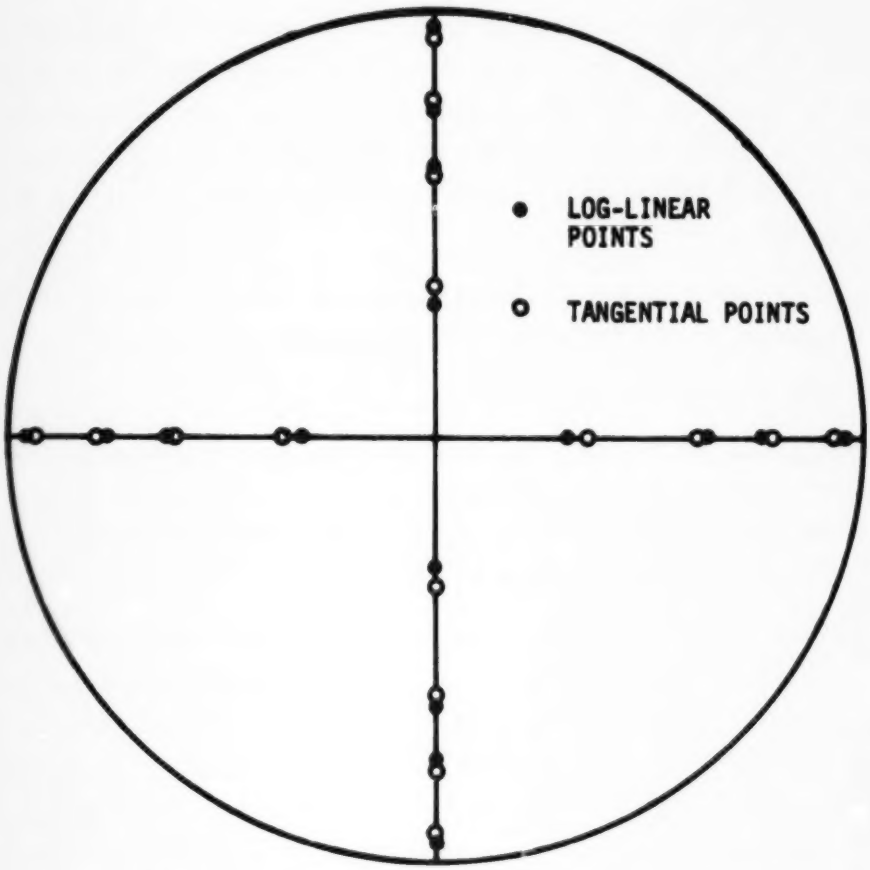


Figure 9. Locations of sample points for tangential and Log-Linear methods - 16 point traverse

Point	1	2	3	4	5	6	7	8
Location Tangential	3.3	10.5	19.4	32.3	67.7	80.6	89.5	96.7
Log-Linear	2.1	11.7	18.4	34.5	65.5	81.6	88.3	97.9

Table 4. TANGENTIAL AND LOG-LINEAR SAMPLE POINT LOCATIONS FOR 16 POINT TRAVERSE IN PERCENT OF DUCT DIAMETER FROM INSIDE WALL TO SAMPLE POINT

The accuracy of the probe location should be on the order of ±0.2% of the corresponding duct dimension. Alignment of the gas sampling probe is not critical, but care should be taken to insure that the velocity sensor is always lined up parallel to the duct axis to minimize flow angularity errors. Such errors can easily reach a magnitude of 5% or more, as is discussed in Section 5, so proper alignment is a very critical item.

- Interference Between Velocity and Gas Sampling Probes - With some combination velocity measurement/gas sampling probes, the velocity probe response is affected by whether or not a sample is being drawn. This is easy to check for, and should it prove to be the case that the velocity is affected, the unit should be calibrated without a sample being drawn, and in actual use, no sampling should be performed while a velocity measurement is being taken. If separate velocity and sampling probes are used, care must be taken to avoid interference effects.

- Leakage - Good seals must be provided around all probes to minimize errors due to leakage. The necessity for good seals increase in inverse proportion to the duct dimensions. If the duct pressure is below ambient, leakage will create air jets into the duct, which will disturb the velocity profile along the line of interest, and can lead to gross sampling errors at points near the leak. If the duct pressure is above ambient, the gas composition will not be greatly affected, but velocity measurement errors will occur near the port. O-ring seals are generally the most reliable and easiest to work with. Probes with unusual cross sectional shapes which are difficult to seal around should be avoided.

- Traverse Times - As mentioned above, it should not be a problem to conduct 16 point traverses in about 20 minutes for velocity, and in less than an hour for gas samples. These times must be minimized to avoid errors due to temporal variations, but rushing which results in sloppy

placement, misalignment, and leakages cannot be tolerated. Times can be minimized by insuring that all equipment is in proper working order and all test personnel are thoroughly familiar with the test setup and procedures. The time response of the gas sampling system must be determined in order to avoid taking too much or too little time at each sampling point. This response time will be a function of the size and length of tubing used, the flowrate and pressure drop along the sample line, and the response time of the analyzers or other equipment used. Velocity traverses can be performed much more quickly because the system time response is practically instantaneous.

- Proportional Sampling - Proportional gas sampling is not considered to be a requirement. This was discussed in Section 3 and is treated in detail in Reference 2. This allows for the use of separate velocity and sampling probes and even separate sampling arrays, as discussed earlier in this section. If a combined velocity/gas sample probe is used, there is no reason not to sample proportionally, but if separate probes are used, it would be advantageous to conduct several velocity traverses during the gas sample traverse, as discussed in the following paragraph.

- Repeatability Data - Sixteen point traverses, especially for velocity, can be conducted quickly enough to allow for procurement of a significant amount of repeatability data. The proper amount of repeatability depends upon the test objectives, economic and manpower factors, and the consistency of the data obtained. If possible, at least three traverses should be performed for each operating condition of interest. Multiple velocity traverses performed during the course of a gas sample traverse are a good check on the validity of the gas sample data — if a significant change in volumetric flow occurs during the course of a gas sample traverse, the gas sampling data will almost certainly be non-representative. If successive traverses show changes near the sample ports but not elsewhere, there are probably errors due to

leakage. Multiple traverses are needed to verify constancy of flow conditions during the period of the traverse, and also to check for errors at individual sample points due to mistakes.

4.2 CONTINUOUS SAMPLING

4.2.1 Single Point Sampling

Single point sampling cannot be recommended if good accuracy is desired except in a straight circular duct when the sensors can be placed at least twenty diameters downstream and five diameters upstream of significant flow disturbances. This type of condition is most likely to occur in pipelines or tall stacks, but is not typical in most stationary source process streams. A long straight run is required for full development of velocity profiles, and a long run with no chemical reaction or addition of mass is needed to avoid gas stratification. There is little question about the need for multiple point velocity measurement, but there is serious controversy over the adequacy of single point gas sampling, so it is worthwhile to consider it in some detail. Acceptability of single point gas sampling depends primarily on two factors: the desired measurement accuracy and the extent of compositional stratification in the sampling plane. It is of course possible that a highly stratified flow could exist in which a constant relationship would exist between composition at a specified point and the average composition, but no evidence of this has been discovered in the data which TRW has examined. As a rule of thumb, it can be said that if the stratification level of the gas stream is higher than the desired measurement accuracy, single point gas sampling will not be acceptable. To make this assessment, a workable definition for "stratification level" must be found, since there is none in common usage.

In order to determine stratification levels from various sources in a consistent manner, a uniform method to determine measures of data spread is required. Perhaps the most common and easy to work with measure of spread is the standard deviation for a normal distribution. The potential problem with using standard deviation as a measure of spread is that it is normally applied to a number of measurements of the same parameter, such as repeated measurements of the length of a table top, or repeated

measurement of gas composition at a single point in a uniform gas stream. For the present case, we wish to apply it to a number of individual measurements of concentration at separate points in a non-uniform gas stream. For this case, there is no a priori reason to believe that the readings can all be considered to belong to a normal distribution. Gas traverse data have been examined to see if they approximated a normal distribution. Data consisted of 49 point traverses for O_2, CO_2, and NO_x in a coal fired power plant. For each traverse, the mean value and standard deviation of the gas concentration were determined as follows:

$$\bar{\mu}_i = \frac{1}{N}\sum_{n=1}^{N}(\mu_i)_n \tag{36}$$

$$\sigma_{\mu_i} = \sqrt{\frac{\sum_{n=1}^{N}[(\mu_i)_n - \bar{\mu}_i]^2}{N}} \tag{37}$$

where

σ_{μ_i} = standard deviation of μ_i

Results of the calculations are shown in Table 5.

Table 5. COMPARISON OF DEVIATIONS FOR ACTUAL AND NORMAL DISTRIBUTIONS

DEVIATION	NORMAL DISTRIBUTION	ACTUAL DISTRIBUTIONS		
		NO_x	CO_2	O_2
σ	68.3	65.3	61.2	71.4
2σ	95.4	100	100	89.8
3σ	99.7	100	100	100

Data are for actual distributions taken from a TRW field test.

Tabular values are percentage of data points which differ from the mean value by less than the specified deviation.

Results in each case are very close to what would be expected for a normal distribution.

Given the validity of the standard deviation as a measure of spread, we can now define a parameter to indicate the degree of stratification in a stream. For most engineering applications, a 95% level of certainty with regard to the accuracy of a measurement is acceptable. This corresponds to a band of $\pm 2\sigma$ about the mean value. Consider the NO_x traverse used for Table 5 as an example. The mean concentration was 734 ppm with a standard deviation of $\pm$26 ppm, or 3.5%. By definition, then, we will say that the stratification level was $\pm$7% (i.e. 2σ) from the mean, which means that the probability is 95.4% that a point measurement taken anywhere in the sample plane will deviate from the mean concentration by less than $\pm$7%. Stratification level is being defined as $\pm 2\sigma$ from the mean concentration value in the sampling plane.

This definition of stratification level is desirable because it fits in directly with the error analysis in Section 3, which is also based on standard deviations. This allows the effect of stratification on system accuracy to be determined in a simple, meaningful manner. For the 26 gas sample traverses previously cited, the stratification level, 2σ, of the actual data points varied from 7% to 36% of the mean concentration, with an average of 15%. By definition, the stratification level is an indication of the accuracy which can be achieved with a single point measurement. The most common single point gas sampling location is in the center of the duct. For the 26 runs, the average 2σ error for a single point measurement at the center of the duct was 13.6%, which is very close to the average stratification value, and very high with respect to the other errors identified in Section 3. On the basis of available data, then, it has been concluded that single point gas sampling will severely degrade achievable system accuracies. If installation of a single point continuous gas monitor is anticipated, the stratification level at the selected site should be determined by full manual traverses. From analysis of accumulated data, we have concluded that for accurate measurements, single point gas sampling is unacceptable for a specific site unless proven otherwise.

4.2.2 Multiple Point Sampling

Multiple point continuous sampling is very distinct from multiple point manual sampling in a practical engineering sense. Large arrays of point sensors for continuous monitoring would be very expensive to procure and maintain. This makes it imperative that the number of sampling points be minimized, so long as large errors can be avoided. Previous discussion has shown that from an accuracy standpoint, a sixteen point array would be quite acceptable, and that a single point sample would generally be inadequate. The number and location of points for a given installation should be determined by the best balance of cost and system accuracy. The methodology presented in this section has been selected to achieve this optimization. The methodology also presumes the use of continuous gas analyzers, electrical outputs for all sensors and analyzers, and the availability of a low cost computer to perform calculations of the kind shown in equation 20. This hardware is discussed in Section 5.

4.2.2.1 Continuous Sampling in Circular Ducts

For monitoring in circular ducts, the site selection criteria are the same as for manual sampling, as discussed in Section 4.1.1. Extensive laboratory testing described in Reference 1 showed a 2σ mapping error of less than 7% for average velocity using the Log-Linear method with eight points (four points on each of two orthogonal diameters), and a 2σ mapping error of less than 9% for average velocity using the Ellison Annubar (a non-point sensor described in Section 5) as the velocity sensor. Each of these errors is larger than the nominal 6% single point accuracy previously cited, but not prohibitively so. In addition, the laboratory testing was conducted using primarily "worst case" flows, so that the expected accuracy in most field situations would be better than the cited figures.

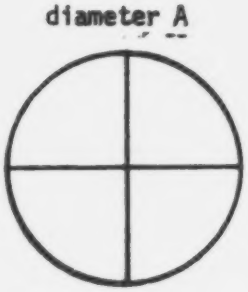
Gas stratification has not been studied as extensively as velocity stratification in circular ducts. An eight point gas sample traverse

using the tangential method is considered to be acceptable on the basis of present knowledge, with the option that the eight points can be taken on either one or two diameters. If one diameter is chosen, it should be the one along which the greatest stratification is observed during preliminary manual traverses. The most important practical point to remember about gas sampling is that work cited in Section 3 shows that it is unnecessary to sample proportionally. This means that the velocity and gas sampling components can be totally independent and the gas sampling rate should be the same at each sample point. The uncoupling of velocity and composition measurements clearly offers the prospect of much lower system cost and complexity.

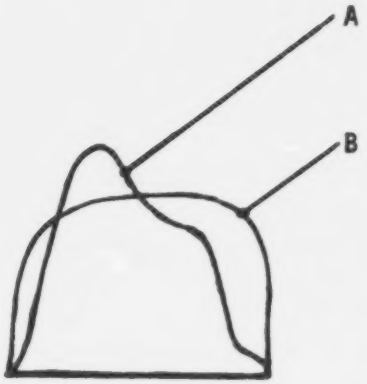
Planning and setting up a multiple point monitoring system in a circular duct should involve the following methodological steps:

1. Select the site so that, as nearly as possible, 80% of the local straight run is upstream of the sample plane.
2. Perform a preliminary traverse at each operating condition of interest to check for unusual velocity patterns and to determine compositional stratification levels.
3. Determine whether or not single point gas sampling is acceptable.
4. Select the number and determine the location of sampling points. Information for locating points using the Log-Linear and tangential methods and the Annubar is shown in Figure 10.
5. Calibrate the system in place using 16 point velocity and gas sample traverses, preferably using at least three traverses for each operating condition. In-place calibration is essential to minimize systematic errors which must be expected due to the small number of sampling points used for the continuous measurements.

The proposed approach for continuous sampling in circular ducts follows directly from the procedures used for manual sampling – the only significant differences deal with the number of sample points involved and the use of spatial rather than flow proportional gas sampling at the selected points.



Duct cross-section



Velocity profiles

For eight point samples using two diameters, locate points along each diameter as follows:

Point	1	2	3	4
Location				
Tangential(gas sample)	6.7	25.0	75.0	93.3
Log-Linear(velocity)	4.3	29.0	71.0	95.7

Locations given in percent of duct diameter from inside wall to sample point

For Annubar use or eight point samples using one diameter, select diameter along which velocity is more irregular (diameter A for the example above), and the diameter along which composition waives the most for velocity measurement and gas sampling, respectively. Point locations are given in Table 4.

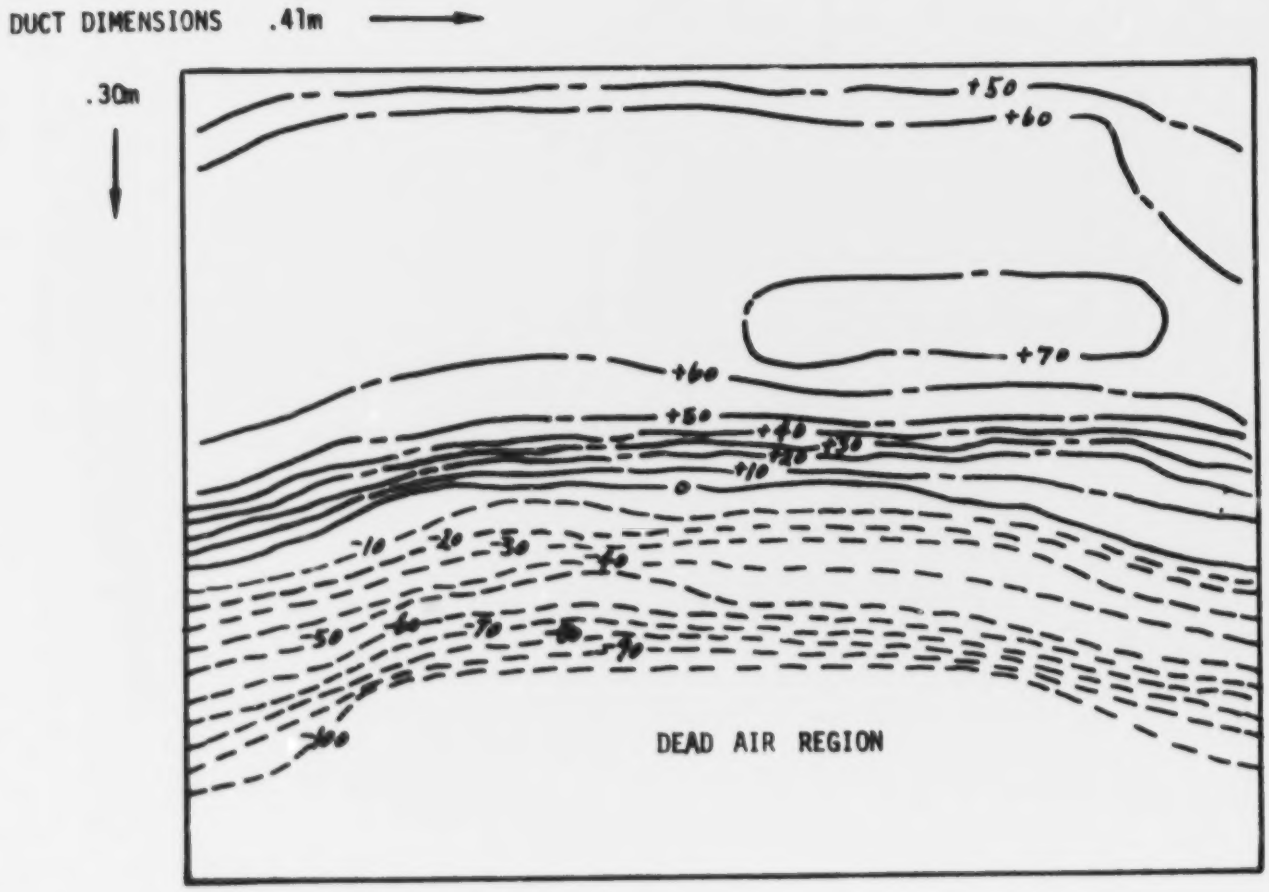
Figure 10. Circular duct continuous monitoring locations

4.2.2.2 Continuous Sampling in Rectangular Ducts

Unlike the circular duct recommendations, the proposed rectangular duct continuous sampling techniques are significantly different from the corresponding manual methods. The differences are due to the nature of velocity patterns in rectangular duct systems and to practical considerations such as cost. A brief discussion of the former is given to serve as an introduction to the proposed sampling techniques.

Velocity measurement methods in circular ducts may be characterized as line averaging techniques, since they involve taking a number of measurements along a line (diameter). The success of a given method depends upon two factors: the ability to obtain an accurate average along the selected line, and the relationship between the average velocity along the line chosen and the average velocity in the entire duct. Common techniques are concerned almost solely with the first factor, and assume a one-to-one correspondence for the second. The basis for this assumption is that fully developed flow in a circular duct is in fact axisymmetric, and a circular duct will automatically condition the flow toward axisymmetry.

It would be desirable to have an analogous situation occur in rectangular ducts, so that a line average across the duct would be representative of the total flow. In practice, this desire is hampered by the fact that in most stationary source streams, the straight runs of rectangular ducting tend to be very short. This inhibits the development of predictable flow patterns, which in turn makes it difficult to develop techniques to accurately measure the flow through use of a small number of sampling points. Fortunately, there is one situation in which the flow is developed in a desirable manner for use of line averaging techniques, and it is a very common one. Immediately downstream of a rectangular elbow, the flow tends to become conditioned so that profiles taken across the duct in the plane of the elbow are very similar as illustrated in Figure 11. The elbow itself constitutes such a violent disturbance to the stream that the profiles tend to be very repeatable with respect to each other regardless of changes in flow further upstream. This property aids in obtaining good repeatability and minimum random error due to flow pattern changes. Due to the nature of the flow downstream of a rectangular elbow, however, the



PROFILES ARE VARIATION IN 10% INCREMENTS FROM MEAN VELOCITY
MEASURED MEAN VELOCITY = 16.0 m/sec

Figure 11. Normalized velocity distribution downstream of an elbow - TRW pilot scale test

desirable flow pattern shown in Figure 11 is very much a function of distance from the elbow. The flow reaches an optimum pattern about one duct width downstream of the elbow, where the duct width is the dimension in the plane of the elbow, and then changes into a much less desirable shape further downstream, as illustrated in Figure 6. Since elbows are such a common occurrence, considerable laboratory development has been performed to make use of their known properties. This work is described in detail in Reference 1, and the end result was the Row Average Method, which allows the use of hardware that is not more complicated than that required for measurements in circular ducts. The Row Average Method was developed for velocity measurements, but has also been shown to be adequate for gas sampling.

The Row Average Method is very simple in concept, but in practice usually requires more preliminary work (i.e. manual traverses) than do corresponding circular duct techniques. The Row Average Method is illustrated in Figure 12.

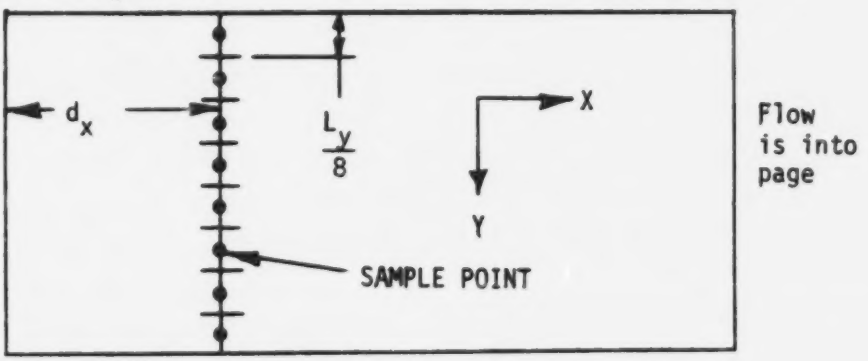


Figure 12. Point locations for row average method

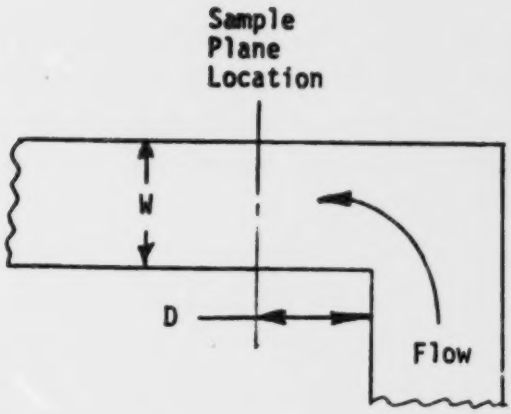
The first step is to select the sample plane location, which will be influenced by the local duct geometry. The second step is to select the appropriate direction, X or Y, in which to take the Row Average. The third step is to select the optimum distance from the wall, d_x, for the sampling line. Once the line has been selected, it is divided into a number of equal segments (eight or more) and the sample points are located at the center of each segment. The output is the average of the individual readings.

The advantages of the Row Average Method are practical ones. Taking all measurements along a single straight line allows for minimum hardware complexity, including an extremely simple approach to gas sampling discussed in Section 5. The penalties to be paid compared to a 4 x 4 array would be a probable higher system mapping uncertainty and a need for greater initial manual investigation to select an optimum site. It is our belief that in most cases the system error can be made small enough to be acceptable. The general procedure for use of the Row Average Method is as follows:

1. Site Selection - Select a location downstream of an elbow if possible. If such a location is available, determine the position of the sampling plane from Figure 13. Note that there are two different locations given, depending upon whether the Annubar or a point array is used for velocity determination. Optimum location will produce local velocity profiles similar to those in Figure 11. If an elbow is not available, the sample plane should be selected so that 80% of the local straight run is upstream of the sample plane.

2. Determination of Row Direction - After the sample plane has been selected, perform reference traverses to determine velocity and concentration maps. For these traverses, it is preferable to use 6 x 6 to 8 x 8 arrays. Using traverse points, compute line averages in each direction and plot the results. Typical results are shown in Figure 14. The direction which should be selected for row averaging is the one which has the flatter profile (X direction in Figure 14). This direction may be different for velocity measurement and gas sampling.

3. Determination of Row Location - Two factors influence this decision unless the Annubar is to be used as the flow sensor. If the Annubar is to be used, it should be located midway between the walls. The two factors are flatness of the row average curve in the vicinity of the proposed row location and deviation of the Row Average from the overall average. The first deals with random errors in that the flatter the local profile is, the lower will be the random error due



A. For Systems Using Annubar, $D = 1.5W \begin{matrix} +.25W \\ -.75W \end{matrix}$

B. For Systems Using Row Average Method for Velocity $D = .8W \begin{matrix} +.40W \\ -.60W \end{matrix}$

Figure 13. Recommended sample plane locations downstream of a rectangular elbow

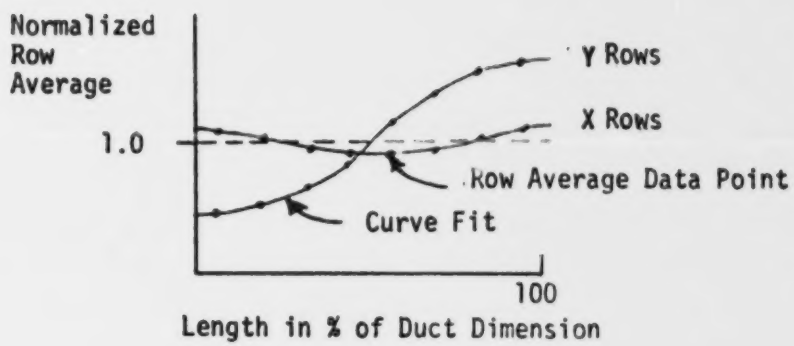


Figure 14. Typical plot of normalized row averages

to flow variations. The second is associated with systematic errors. The first factor should usually take precedence since systematic errors of this type can be eliminated through in-place calibration. A desired row location is illustrated in Figure 14.

4. Installation and In-Place Calibration - After the row locations have been selected (they will be presumably different for velocity and gas sampling) the hardware can be selected and installed, with a minimum of eight sample points along each Row. The system should then be calibrated in place by means of 16 point velocity and gas sample traverses. At least three traverses should be performed at each flow condition. In place calibration is essential to minimize systematic errors.

The Row Average Method is recommended because it has demonstrated acceptable accuracy in the laboratory and in the field, and because it results in minimum cost and system complexity. Like the proposed circular duct techniques, it makes use of the uncoupling of velocity and concentration in the sample plane.

4.2.3 General Sampling Considerations

Many of the comments in Section 4.1.3 on manual sampling apply as well to continuous monitoring. In addition to those, the following should also be given appropriate consideration to assure accurate, reliable measurements:

- Selection of In-Stream Components - This will be covered in more detail in Section 5. The emphasis should be placed on purchasing or fabricating components whose performance will not be degraded due to long term exposure to the flow stream. For example, the effect of particulate buildup on aerodynamically important surfaces of velocity sensors is not usually a problem for manual traverses because of the short exposure times involved. For long term applications, the effect of the buildup would tend to appear as a systematic shift in output which may be overlooked if the sensor

continues to function. In a case such as this, the system should not be calibrated in place until a steady state buildup is reached, so that the calibration will be appropriate for subsequent data.

- Probe Locations and Alignment - The important point here is to use proper hardware (e.g. fittings) and installation procedures to insure that proper probe placement and alignment are maintained after installation. Process stream ducting is usually subject to continuous vibrations which could easily result in movement or rotation of in-stream probes. In addition, once probes are installed the locations should be permanently marked in such a manner that the probes can be removed for maintenance and then replaced in exactly the same location. This must be done to avoid compromising calibration data previously obtained.

- Leakage - Proper fittings should be used to avoid leakage problems in pressure and gas sample lines. We have had the best experience with Swagelok fittings, which are designed to resist loosening due to vibration and can be repeatably connected and disconnected without degradation. Pipe thread fittings should be used as little as possible, and only with a proper thread sealant such as Teflon tape. Leakage problems in gas sample lines can be minimized by maintaining as much of the line as possible at higher than ambient pressure.

- Data Reviews - Regular, methodical reviews of system output data are a good way to discover system errors. For example, a steady change in output over an extended period of time when flow conditions are known to be constant indicates the development of a systematic shift.

- Accuracy Considerations - The proposed sampling techniques are intended to give significantly better system accuracy than the currently popular single point techniques, while avoiding the cost and complexity of large arrays. The possibility of having a system with a systematic error perhaps

as high as 10% due to the sampling configuration selected is considered acceptable due to the fact that such an error can be eliminated through in-place calibration. It is large random errors which cannot be tolerated, since they cannot be reduced. The body of data available for Row Average and Log-Linear velocity measurements with 8 points, and for the Annubar, suggests that acceptably small random flow variations can be expected for a given installation due to the stabilizing effects of the local geometry on the flow distribution. It is our belief that for most installations, the 2σ random error due to flow and composition variations should not be greater than $\pm$6% and $\pm$4%, respectively, which is roughly twice the error expected for a properly performed 16 point traverse.

Basic continuous measurement system procedures are given in Section 6.

5. HARDWARE

This section is concerned with the characteristics of velocity measurement hardware for manual and continuous applications, and with devices used to obtain gas samples. It is not specifically concerned with gas sample train components which are not in the stream, but several of these are discussed briefly. The purpose of the section is to show the acceptability or unacceptability of various pieces of currently available hardware, to indicate where hardware development is needed for continuous monitoring systems, and to show a prototype monitoring system which incorporates the proposed methodology and hardware.

5.1 VELOCITY MEASUREMENT

5.1.1 Pitot Devices

Pitot probes of various types are used to sense velocity by means of the relation in Equation 3. An extended treatment of the subject is given in Reference 12. Two probe characteristics are of primary importance for stationary source monitoring — calibration factor when the probe is aligned with the flow, and sensitivity to flow orientation angle. The two most common types of pitot probes are the pitot-static probe, Figure 15a, and the Stauscheibe or S probe, Figure 15b. The primary output of each probe is the pressure difference between the high and low pressure ports. It is common practice to associate a calibration factor K with the probe such that

$$K = \sqrt{\frac{\Delta p}{\Delta p_x}} \tag{38}$$

where

K = calibration factor, dimensionless

Δp = true free stream differential pressure, $p_o - p_\infty$, torr

Δp_x = measured differential pressure from instrument

A typical calibration curve is shown for a commercially available S probe in Figure 16.

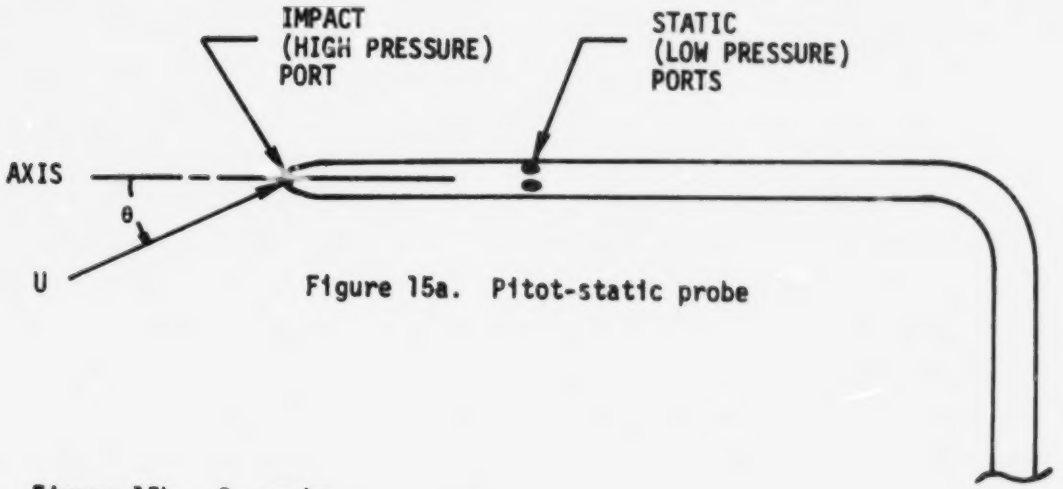
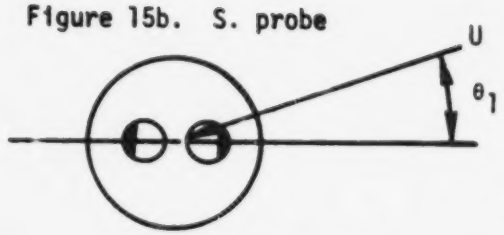
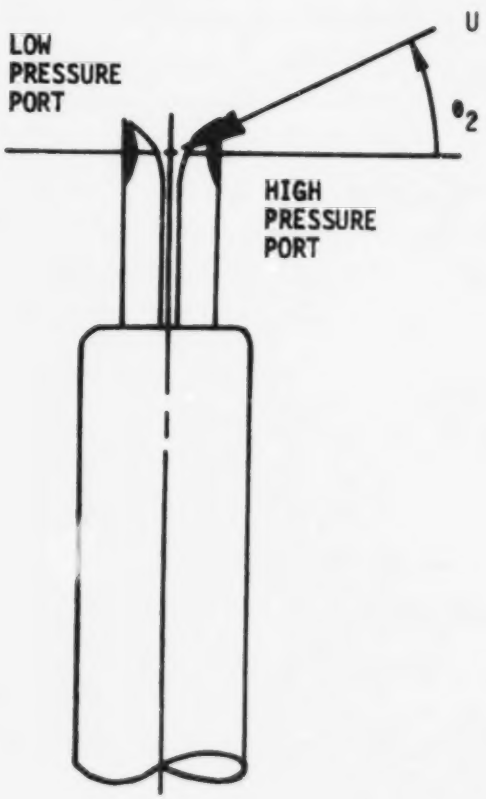


Figure 15a. Pitot-static probe

Figure 15b. S. probe





For the pitot-static probe, orientation can be specified by one angle, θ, due to the axisymmetry of the probe. For the S probe, orientation is a function of two independent angles: θ_1, the rotation angle and θ_2, the tilt angle.

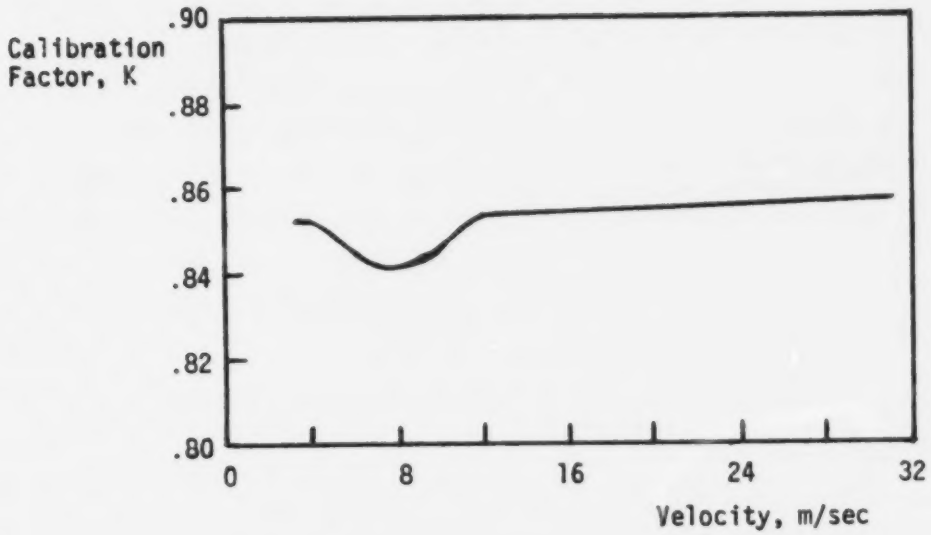


Figure 16. S probe calibration factor as a function of velocity

There are S probes which have more constant calibration factors than the one shown in Figure 16, but users must be cautioned not to assume a constant calibration factor for a given probe — they should be calibrated individually to verify the true calibration.

There are several forms of pitot-static probes, the most desirable of which for process streams use is the ellipsoidal nosed pitot-static probe. The following statement regarding calibration accuracy is taken from Reference 12, page 35, based on a calibration factor K = 1.000: " .... it seems reasonable to assume that the maximum error on velocity will not exceed 0.5 per cent over the entire speed range from 3 to 200 ft/sec." The upper limit of the range is determined by compressibility effects, and the lower end is proportional to the probe diameter. The statement applies specifically to probes of diameter .79 cm (.31 inches), so that a probe of diameter .64 cm (.25 inches), which is a commonly available size, would have a lower limit of 1.1 m/sec.

In terms of calibration factor above, a properly designed S probe with a constant calibration factor would be preferable to a pitot-static

probe because of the higher differential pressures it produces. When orientation sensitivity is also considered, the preference changes. An orientation sensitivity plot for the same commercially manufactured S probe is shown in Figure 17, which shows TRW test data taken from Reference 1. Figure 17 shows that orientation sensitivity is a function of velocity as well as angle. Comparison data for the S probe and ellipsoidal nosed pitot static probe are given in Table 6, where the pitot-static probe data are from Reference 12. The angles are defined in Figure 15.
The angles are defined in Figure 15.

TABLE 6. YAW CHARACTERISTICS OF PITOT-STATIC AND S PROBES

θ Degrees	Error with Respect to $u = U \cos \theta$, %		
	Pitot Static Probe	S Probe	
		Rotation Angle, θ_1	Tilt Angle, θ_2
0	0	0	For $\theta_2 > 0$, errors are higher than corresponding θ_1 errors; for $\theta_2 < 0$, errors are of the same order as θ_1 errors.
5	+.6	+3.3	
10	+2.0	+6.9	
15	+3.3	+7.4	
20	+2.7	+9.0	
25	+1.7	+11.9	
30	+.3	+15.0	

The entries in Table 6 are exactly in the form of the error term $[(\tan \theta)\sigma_\theta]$ in the error analysis equation, Equation 24a, so that the effect on system accuracy can be easily determined.

The accuracy savings offered by the higher pressure output of the S probe are more than offset by the large errors due to alignment sensitivity. Field measurements taken with S probes traditionally tend to result in overly high estimates of average velocity, and orientation sensitivity is believed to be the cause. The S probe is unquestionably a good instrument for qualitative investigation work, since its bi-directionality

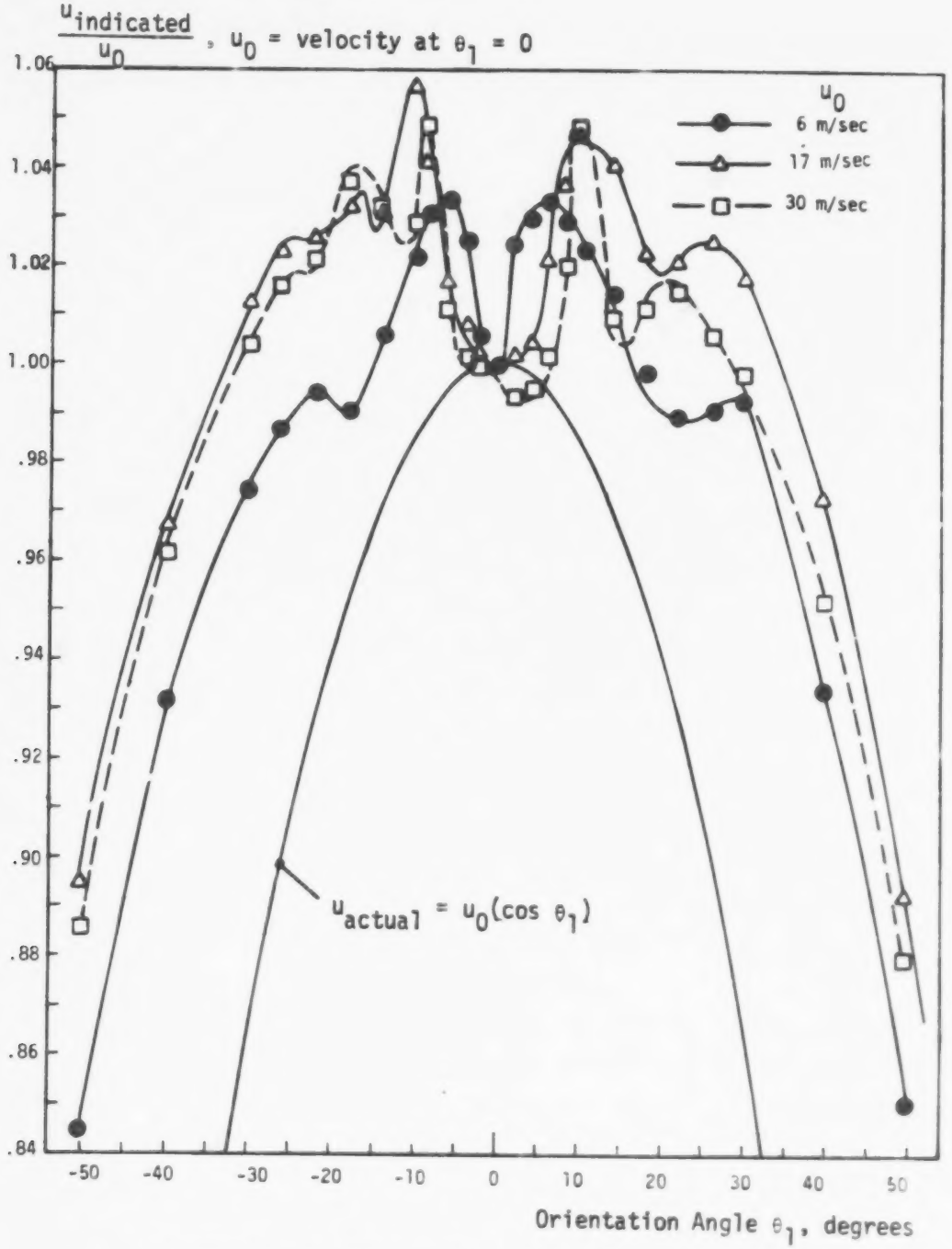


Figure 17. S pitot probe orientation sensitivity data

quickly reveals such things as recirculating regions in the flow. For quantitative work, however, the pitot-static probe is much more desirable because of its accuracy characteristics. The S probe is suitable for quantitative work only when very good flow alignment with respect to the duct axis can be verified, as in the case of a long, straight circular duct with no swirl. TRW test teams have used pitot-static probes for manual traverses in field applications involving high particulate grain loadings and in very moist, droplet laden streams without encountering clogging problems. Some care is required to avoid bending the probe head during insertion and withdrawal, but this does not hamper operating efficiency. EPA Method 2 recommends that a pitot-static probe be used to calibrate S probes. After examining and working with both types of probes, we have concluded that the S probe is unacceptable for accurate work under most circumstances, and the "primary standard" – the pitot-static probe – should be used instead.

5.1.2 Continuous Monitoring Velocity Instruments

In this section, two instruments which are known to be acceptable are discussed. In addition, an unacceptable instrument is briefly discussed, and general criteria for instrument selection are presented. Finally, some advanced types of instruments are mentioned to indicate desirable directions for future development.

5.1.2.1 Ramapo Fluid Drag Meter

The Ramapo Mark VI Fluid Drag Meter is shown in Figure 18. The drag force on a target disc is measured, and velocity is calculated from knowledge of the drag coefficient of the disc. Velocity is proportional to the square root of the output in the same way that velocity is proportional to the square root of the differential pressure from a pitot-static probe. The standard probe has a nominal accuracy of $\pm 1\%$ of the measured velocity. This accuracy was confirmed through TRW testing as described in Reference 1. The key to the accuracy of the instrument is the constant drag coefficient of the target disc, which is treated in Reference 13. Instrument calibration can be checked and adjusted electronically through the use of a decade box, which helps to minimize calibration problems. As with the S probe, orientation sensitivity varies as a function of velocity. For the velocity range 10m/sec to 25 m/sec,

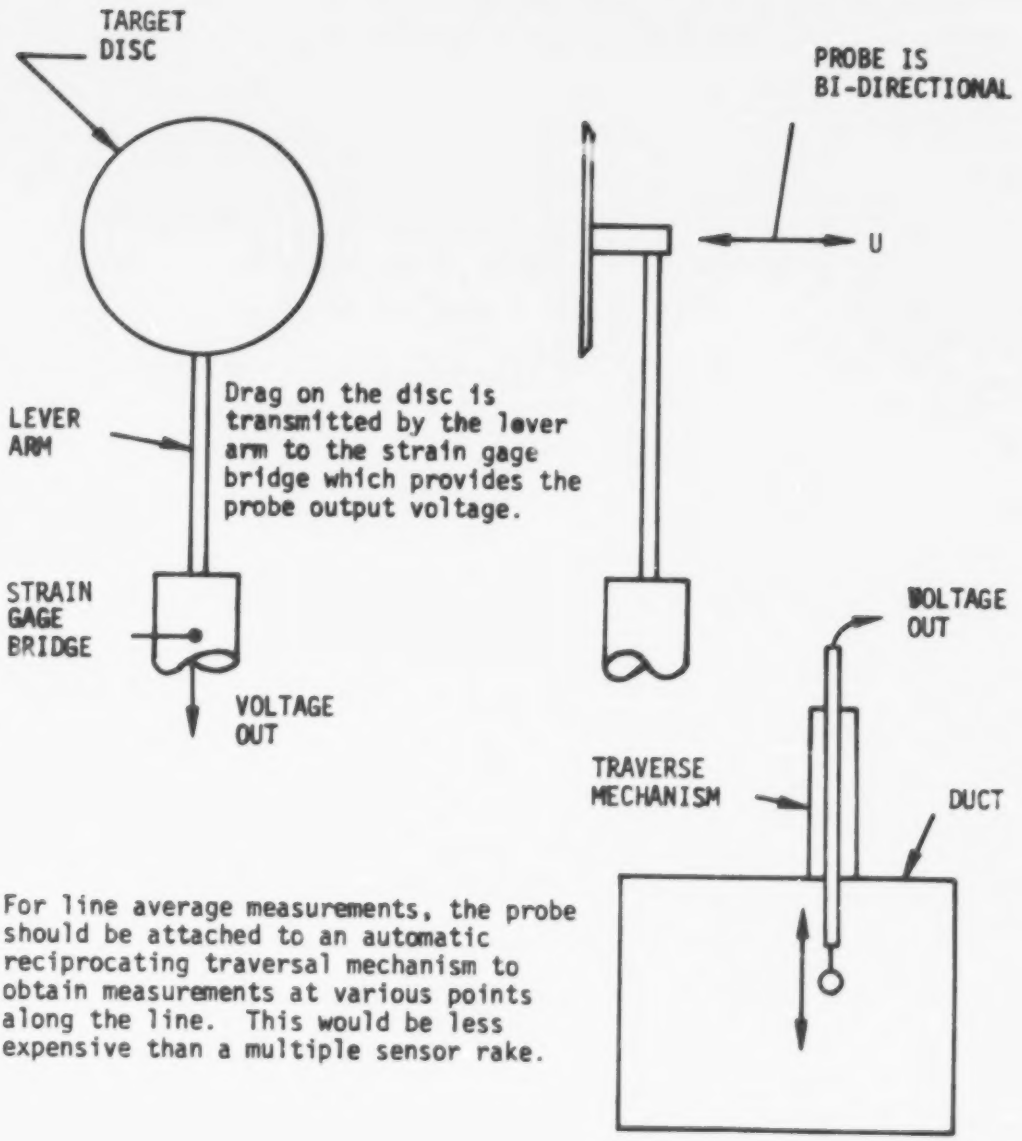


Figure 18. Ramapo Fluid Drag Meter

the maximum error for flow misalignments up to 30° would be about 3%; the figure would be somewhat higher for velocities outside this range.

The instrument is acceptable for long term continuous monitoring because of its desirable accuracy characteristics and because of its ability to withstand hostile flow environments. The only important component which may be susceptible to corrosion over a period of years is the target disc itself, and that component is very inexpensive. The probe requires only electricity – no purge gases or compressed air is used.

The Ramapo Fluid Drag Meter was found to be the best of the point sensors tested in Reference 1, and is definitely recommended for use in continuous monitoring applications involving point velocity sensing techniques.

5.1.2.2 Ellison Annubar

The Annubar, mentioned briefly earlier in the report, is shown in Figure 19. As a velocity sensor, the Annubar is somewhat unique because it does not take measurements at a single point but along a line across the duct. The instrument consists of a tube with four holes which face directly upstream, and a single hole on the backside of the probe. The tube is hollow so that the four upstream ports combine to provide a single pressure output, which is then compared to the downstream hole pressure to provide a single differential pressure output. In practice then, the instrument has the same type of output as an S probe, but responds to the flow velocity at five points in the stream instead of one.

The Annubar was developed for use in circular ducts, the impact hole positions being located according to a circular duct mapping scheme. Extensive TRW testing described in Reference 1 has also shown it to be suitable for measurement in rectangular ducts. The primary advantages of the Annubar are practical ones. It has been demonstrated that a single Annubar can achieve accuracies comparable to arrays of up to eight point sensors. Since accuracies are comparable, the advantages of using a single probe with a single output rather than eight sensors with eight outputs are immediately obvious. Testing in the laboratory has resulted in the conclusion that 2σ random errors for Annubars used in short runs of circular and rectangular ducting should be on the order of 3% to 7%, which is comparable to the accuracy of the Row Average Method using eight points.

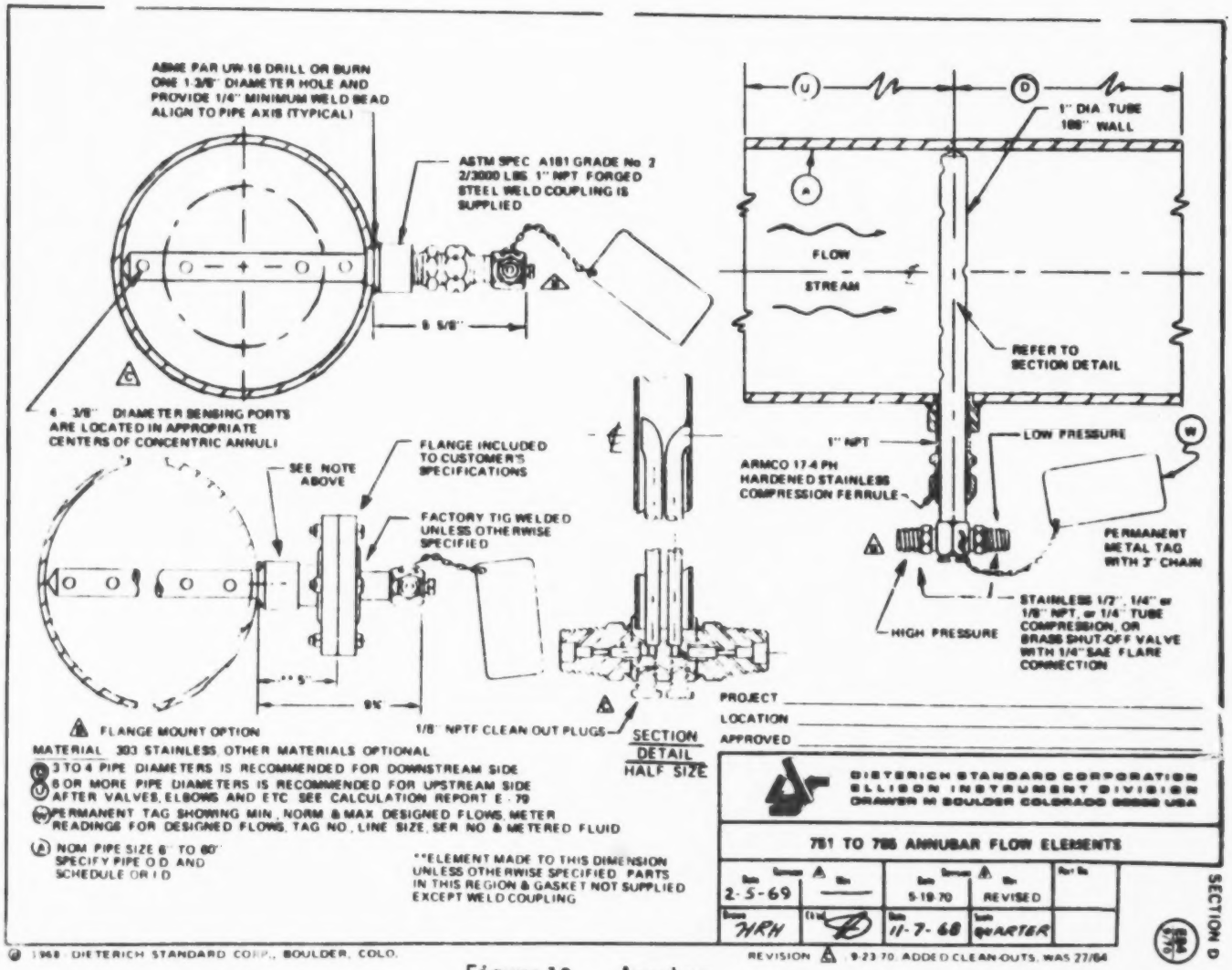

ASME PAR UW 16 DRILL OR BURN ONE 1 3/8" DIAMETER HOLE AND PROVIDE 1/4" MINIMUM WELD BEAD ALIGN TO PIPE AXIS (TYPICAL)
ASTM SPEC A181 GRADE No 2 2/3000 LBS 1" NPT FORGED STEEL WELD COUPLING IS SUPPLIED
6 5/8"
4 - 3/8" DIAMETER SENSING PORTS ARE LOCATED IN APPROPRIATE CENTERS OF CONCENTRIC ANNULI
SEE NOTE ABOVE
FLANGE INCLUDED TO CUSTOMER'S SPECIFICATIONS
FACTORY TIG WELDED UNLESS OTHERWISE SPECIFIED
5"
9 1/2"
FLANGE MOUNT OPTION
1/8" NPTF CLEAN OUT PLUGS
SECTION DETAIL HALF SIZE
MATERIAL 303 STAINLESS OTHER MATERIALS OPTIONAL
3 TO 4 PIPE DIAMETERS IS RECOMMENDED FOR DOWNSTREAM SIDE
6 OR MORE PIPE DIAMETERS IS RECOMMENDED FOR UPSTREAM SIDE AFTER VALVES, ELBOWS AND ETC SEE CALCULATION REPORT E-79
PERMANENT TAG SHOWING MIN, NORM & MAX DESIGNED FLOWS, METER READINGS FOR DESIGNED FLOWS, TAG NO, LINE SIZE, SER NO & METERED FLUID
NOM PIPE SIZE 6" TO 60" SPECIFY PIPE O.D. AND SCHEDULE OR I.D.
**ELEMENT MADE TO THIS DIMENSION UNLESS OTHERWISE SPECIFIED PARTS IN THIS REGION & GASKET NOT SUPPLIED EXCEPT WELD COUPLING
U
D
1" DIA TUBE 188" WALL
A
FLOW
STREAM
REFER TO SECTION DETAIL
1" NPT
LOW PRESSURE
ARMCO 17-4 PH HARDENED STAINLESS COMPRESSION FERRULE
PERMANENT METAL TAG WITH 3" CHAIN
STAINLESS 1/2", 1/4" or 1/8" NPT, or 1/4" TUBE COMPRESSION, OR BRASS SHUT-OFF VALVE WITH 1/4" SAE FLARE CONNECTION
HIGH PRESSURE
PROJECT
LOCATION
APPROVED
DIETERICH STANDARD CORPORATION
ELLISON INSTRUMENT DIVISION
DRAWER M BOULDER COLORADO 80302 USA
751 TO 755 ANNUBAR FLOW ELEMENTS
2-5-69
5-19-70
REVISED
MRH
11-7-68
QUARTER
SECTION D
1968 DIETERICH STANDARD CORP., BOULDER, COLO.
REVISION 9-23-70 ADDED CLEAN-OUTS, WAS 27/64

Figure 19. Annubar

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Like the Row Average Method, the Annubar should be calibrated in place to minimize systematic errors.

The Annubar rear orifice is subject to clogging, as described in Reference 1, so an intermittent purge using compressed air is recommended in particle laden streams, especially when the moisture content is high. Also, buildup of particulate on the back side of the probe can affect the reading of the rear orifice. This accuracy consideration was discussed in Section 4.2.3. Because of this effect, the Annubar should not be calibrated until a steady state buildup has been reached. Purging will not affect the bulk of the buildup, but will just keep the orifice itself clear. In sources such as power plants, this steady state condition should be reached within about 24 hours after installation. A nominal purge cycle would be five minutes per hour.

5.1.2.3 General Considerations for Instrument Selection

Several of the characteristics to be mentioned below will ordinarily be determined from manufacturer's data. The following situation is presented to show that such data must be examined with care to avoid being misled about instrument performance.

A Hastings-Raydist Flare Gas Flow Probe was selected for evaluation as a continuous monitoring probe. The following paragraph is quoted from the factory manual section on accuracy:

> "The initial calibration of the probe is ±2% of the full scale voltage; that is, ±.10 volt. Since the velocity vs. voltage curve is non-linear, the velocity tolerance must be detemined for each segment of the curve. For example, ±.10 volts represent a velocity tolerance at 1000 fpm (2.00 volts) of ±50 fpm, but at 2500 fpm (4.00 volts) it represents ±150 fpm."

After reading this, most people would be inclined to remember only the ±2% figure, and tend to think of the instrument as having a ±2% accuracy, despite the presence of the two qualifying sentences. The accuracy in terms of velocity is shown in Figure 20.

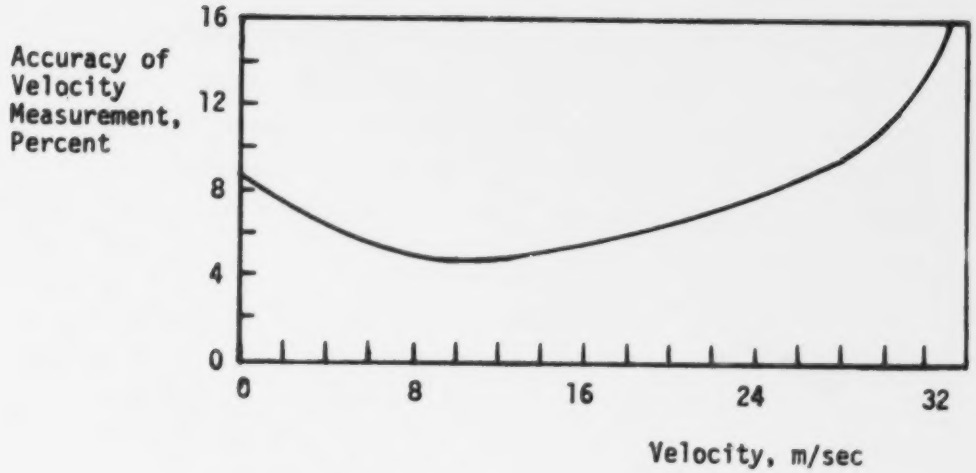


Figure 20. Velocity accuracy for Flare Gas Flow Probe

Accuracy in terms of velocity, which is the real parameter of interest, is not on the order of 2%. The point of the illustration is that accuracy should always be considered in terms of the main parameter, and not a secondary parameter such as voltage.

Selection of a velocity sensing instrument for continuous monitoring applications should involve consideration of the following:

1. Accuracy - This relates primarily to simple straight alignment (θ=0) accuracy but also includes such features as repeatability, drift, zero and full scale stability, and hysteresis. All of the effects should be combined, using the R.M.S. technique exemplified in Equation 23, to produce a single curve of accuracy given as percent of reading, as in Figure 20. This approach avoids possible misconceptions concerning instrument accuracy. When the data are presented in this manner, a determination can be made regarding the suitability of a particular sensor for a specific application.

2. Orientation Sensitivity - This parameter is being emphasized throughout the manual because of its importance in process stream measurements. So long as measurements must be made in ducts of complicated geometry with many disturbances and changes of direction, significant flow angularity will be

encountered. Orientation sensitivity is not a parameter for which manufacturers normally supply data, so the work usually has to be performed by the customer. In any event, this type of calibration may be very important relative to overall system accuracy and should be treated accordingly.

3. Survivability - It is essential that the sensor be able to perform in a process stream environment for long periods of time. Survivability data are usually best obtained from people who have been using the instrument for a prolonged period in application similar to or worse than the intended one.

4. Support and Interface Requirements - Does the instrument require additional devices such as voltmeters or pressure transducers, and if so, what is the impact of these additional devices on cost and system accuracy? It is also important to know the extent of assembly required by the customer after delivery. What type of power interface is required, and does the instrument need compressed air or water supplied to it? Some instruments are very sensitive to changes in line voltage, so it may be necessary to provide a voltage regulation capability to damp out line fluctuations.

5. Maintenance and Calibration - What are the extent and frequency of normal maintenance and calibration? Can calibrations be performed in place, as with the Ramapo Fluid Drag Meter, or will it be necessary to remove the instrument and ship it back to the factory?

6. Cost - A nominal cost breakdown estimate should be performed for a specified period of time. Items included should be the purchase price of all identifiable system components, an estimate of expected replacement costs during the time period, and cost in manhours to assemble, learn to use, install, calibrate, and maintain the equipment.

Any given instrument may have a particular characteristic in any one of the above categories which would make it unsuitable for use, so each category should be considered before making a purchase. It is recommended that the Ramapo Fluid Drag Meter and Ellison Annubar be used as standards for comparison for point sensors and line averaging sensors, respectively, when evaluating velocity devices for a given application.

5.1.2.4 Advanced Concepts

The great majority of currently available instruments are point sensors. Since point sensor arrays are expensive and single point measurements are generally inaccurate, point sensors are not the most desirable type to use for process stream measurements, especially for continuous monitoring. The next major development step should logically be line averaging devices. The Annubar is a good start in that direction. The near future should see development of techniques such as laser anemometry for general industrial applications. A line averaging device should be able to do just what the name implies – measure the average velocity along the line of interest. In a circular duct, such an average would be in error because of the area considerations, but the error would be systematic in nature and could be accounted for by a calibration factor. In a rectangular duct, a line average is exactly what is desired for the Row Average Method. The methodology for line average devices may be said to already exist, at least in elementary form, which lends credance to their development.

5.1.3 Supplementary Velocity Instrumentation

This section deals with pressure and temperature measurements which are usually required in support of velocity measurements. The parameters of interest are differential pressure (nominal range 0-5 torr), absolute static pressure (700-800 torr), and static temperature (0-400°C). Static temperature and pressure are reasonably easy to measure with accuracies on the order of 1% or better, using properly compensated thermocouples and electronic pressure transducers or manometers. Recall from Section 3 that static temperature should be measured at each point where velocity is measured, while static pressure can be considered constant across the duct. In continuous monitoring systems, it is usually not acceptable to assume that static pressure remains constant over long periods of time and use a single value in data reduction. Stream pressures usually change

as a function of ambient pressure, which can change by 3% to 4% over a period of days. Velocity sensors should ideally incorporate integral thermocouples, and should be purchased in that configuration if possible.

Differential pressure measurement is traditionally a source of large uncertainties because of the small pressures involved in gas flow measurements. Electronic pressure transducers are capable of providing accurate measurements in the range of interest, but are more expensive than liquid manometers. In most cases where good accuracy is of interest, the expense will certainly be justified. Nominal accuracies for a U-tube manometer, Statham pressure transducer, and MKS Baratron pressure transducer are shown in Figure 21. The cost for the Statham unit would be about $400, and about $3000 for the Baratron. The Baratron cost is similar to that for a typical continuous gas analyzer. For a continuous monitoring system which employs a differential pressure device such as the Annubar, the velocity measurement error is likely to be the largest single error source, so use of an adequate pressure transducer is essential, just as it is also essential for maximum accuracy of manual traverses.

5.2 GAS SAMPLING

This section is concerned with hardware for extracting gas samples, that is, gas sample probes. Other sample train components are mentioned as necessary in the discussion.

5.2.1 Single Point Sampling Probes

Gas sampling is not subject to the isokinetic requirements which govern particulate sampling, so the shaped nozzle commonly used for particulate sampling is not required. In fact, its use can sometimes lead to sampling errors. The objective in gas sample extraction is to locate the sample probe at the point of interest and withdraw the gas sample without causing any changes in composition or phase of the gaseous stream components. Basically this means that changes in temperature and pressure along the sampling line must be minimized in order to maintain the gas sample at the local stream pressure and temperature. Pressure losses can be minimized by using the largest reasonable size of tubing and low flow rates. The extraction flow rate must of course be compatible with the method of analysis to be used. Temperature control is best provided by having a

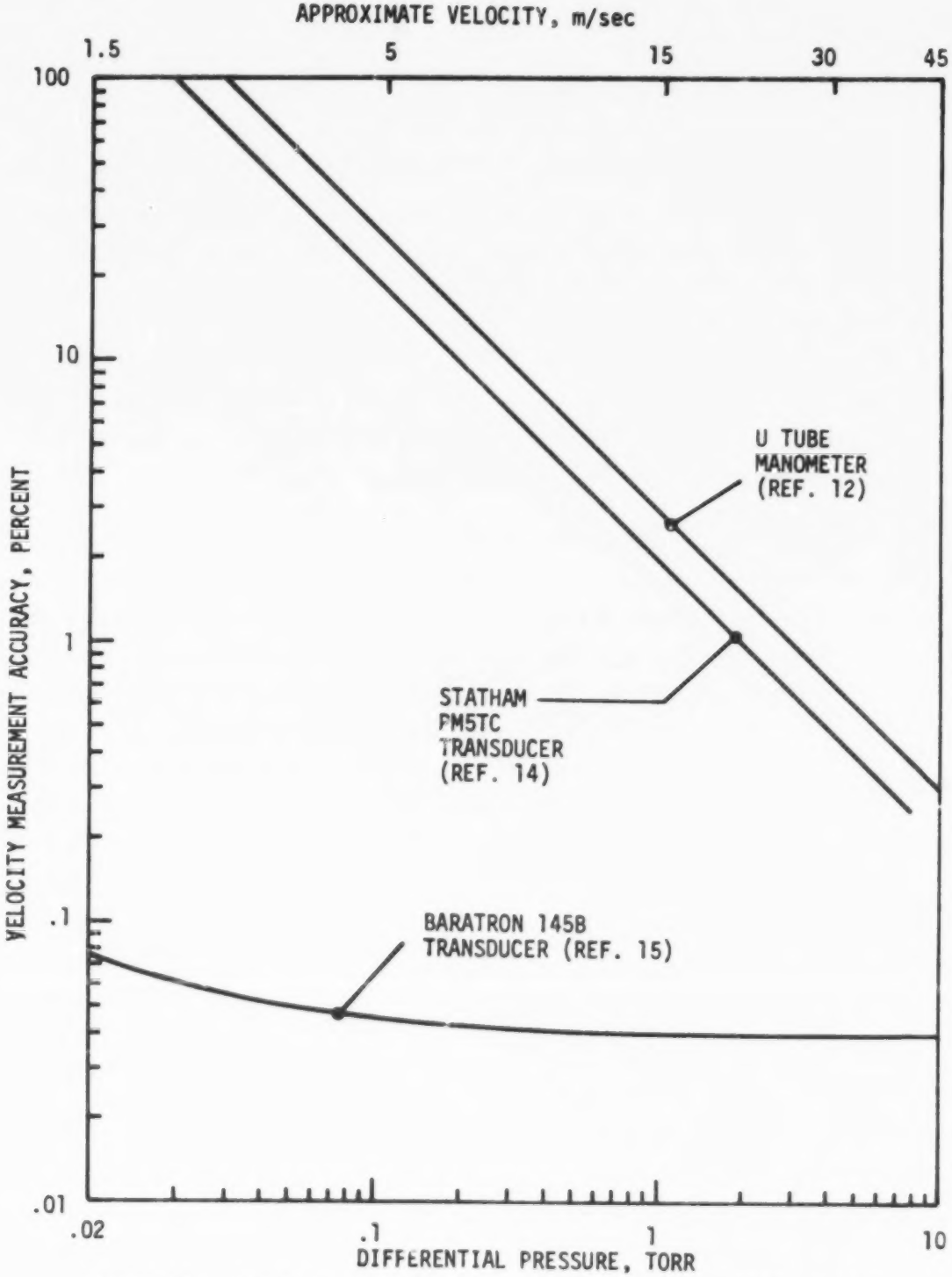


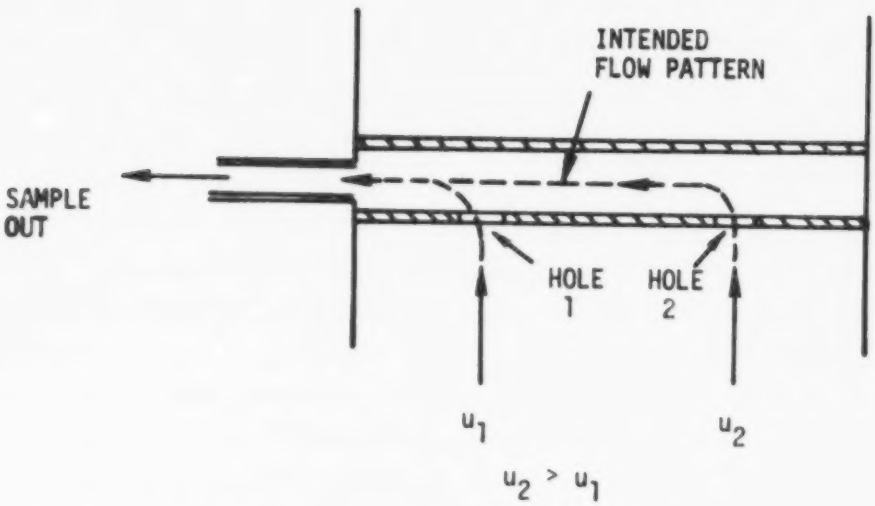
Figure 21. Single point velocity accuracy based on differential pressure measurement accuracy versus differential pressure for three pressure measurement methods

thermocouple at the probe inlet and maintaining as much of the sample line as possible at the probe inlet temperature. Thermal control is most critical for substances such as water and volatile hydrocarbons which may be subject to significant evaporation or condensation in the sample lines.

Aerosol evaporation in the sample lines can best be avoided through use of a sample probe whose inlet is normal to the flow or, preferably, pointing downstream. This will minimize the collection of droplets which could subsequently be vaporized. A particulate filter at the probe entrance should be used to remove any entrained particles. If aerosols are kept out of the sample lines, thermal control of the probe is made easier, since it then becomes a matter of insuring that the line temperature does not fall below the temperature at the probe entrance.

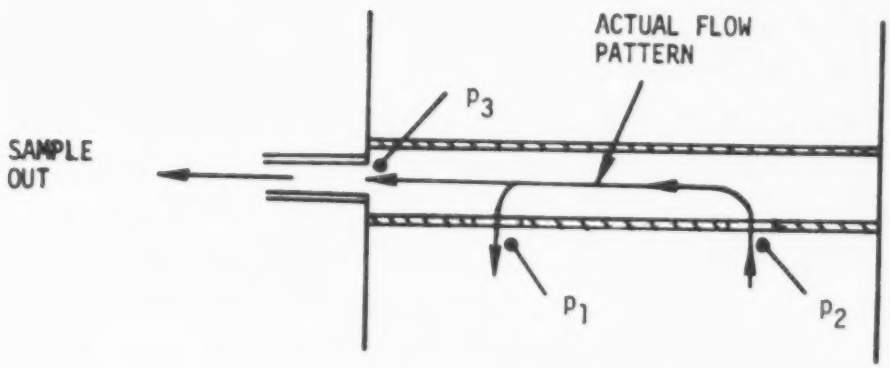
5.2.2 Multiple Point Sampling Probes

Multiple point sampling probes are of interest primarily for continuous monitoring applications, but also may be of value in situations where the process cycle time is too short to allow a manual traverse. There is one fairly common misconception about the operation of multiple point sampling probes which should be disposed of before proceeding further. Consider the hypothetical situation shown in Figure 22a. It is desired to obtain a sample at two points in a stream, where the velocity at one of the points is higher than at the other. A common technique is to use a single sample tube with holes at the two points of interest, and make the hole area proportional to the local velocity. To avoid particulate clogging problems, the holes are made as large as possible. The intent is to draw a sample through each hole in proportion to the local velocity. What will actually happen is quite different. With normal sampling rates on the order of a liter per second and tube diameters of 2 to 3 cm, the pressure drop along the sample tube is very small, and will usually be smaller than the variation in stagnation pressure in the free stream. When this happens, and when the sampling holes are large so that there is very little pressure drop across the holes, the flow pattern in the probe develops as shown in Figure 22b. Because of the relative pressure drops, only flow from the high velocity region enters the probe. Some of it is withdrawn and becomes the sample, while the remainder goes back out of the probe through the



$u_2 > u_1$

A. INTENDED DESIGN: HOLES 1 AND 2 ARE SIZED IN PROPORTION TO u_1 AND u_2 WITH THE INTENT OF OBTAINING A FLOW PROPORTIONAL SAMPLE THROUGH THE HOLES



$p_2 > p_3 > p_1$

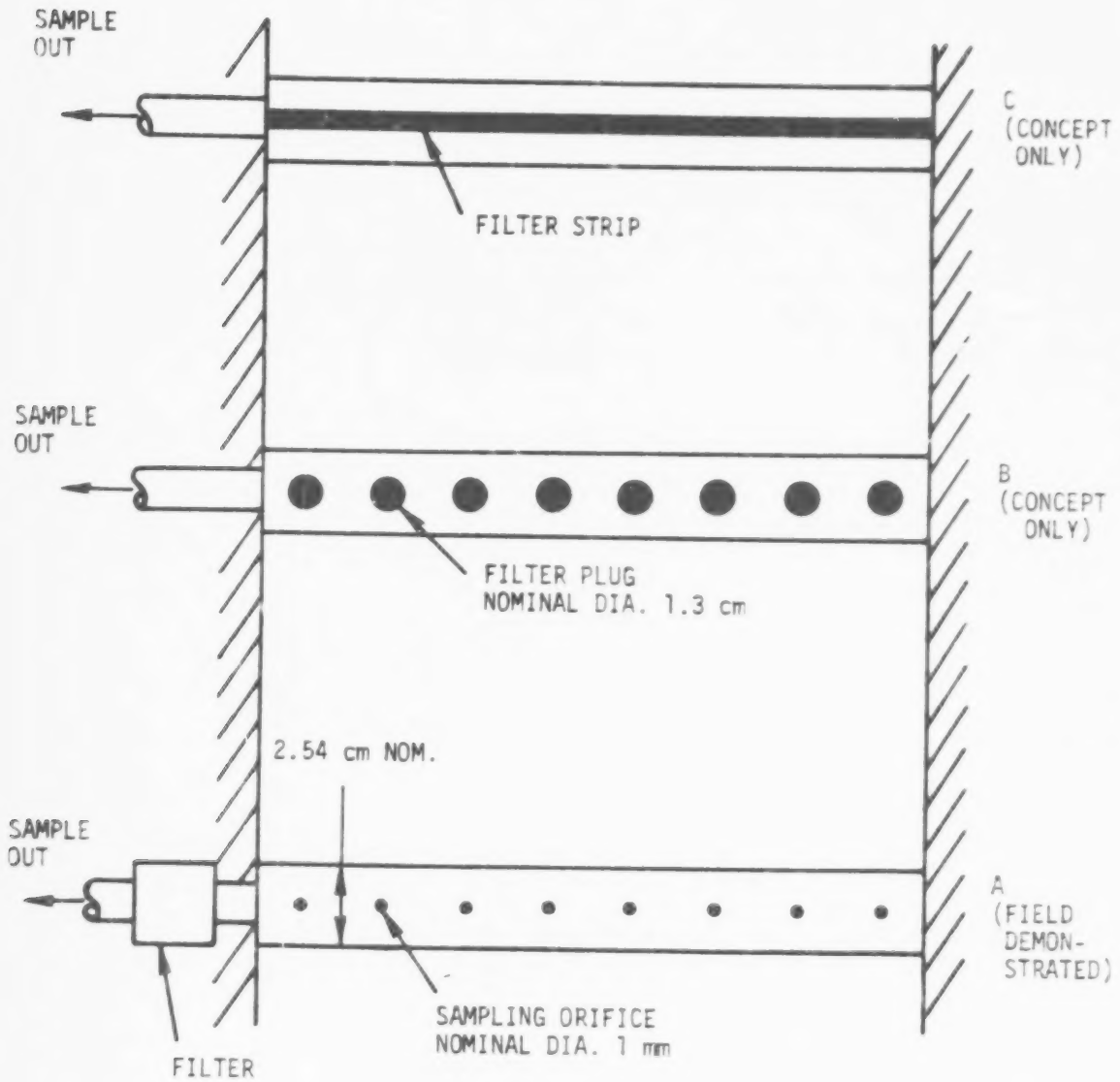
B. ACTUAL OPERATION: FLOW IS PRESSURE DRIVEN. SINCE $p_3 > p_1$, FLOW WILL GO OUT OF HOLE 1 RATHER THAN IN. SAMPLE IS OBTAINED ONLY FROM HOLE 2.

Figure 22. Illustration of multiple point gas sampling misconception

other sampling hole into the lower velocity region. The result is that the extracted sample is not the sample which was intended.

In order for a probe of the type shown in Figure 22 to function as intended, the pressure drop across each sampling hole must be large in comparison to the free stream pressure variations. In most cases, a pressure drop across each sampling orifice of about 20 torr will be adequate to insure proper flow through each orifice. This will typically result in effective orifice diameters of about one millimeter. Prototype sampling probes designed on this basis are shown in Figure 23. The probe in Figure 23a was fabricated and successfully used in proof of principle field test work as described in Reference 2. Its use was limited by the need to clean or replace the in-line filter used to remove particulate from the stream. There were no problems associated with clogging of the orifices themselves despite their small size. More suitable designs are shown in Figures 23b and c. It is highly recommended that such probes be developed as standard commercial items. They are designed so that particulate filters act as the stream interface and provide the pressure drop necessary to insure proper sampling. If the probes face into the flow, the filter elements will tend to be self cleaning, since the impacting stream will help to prevent buildup of particulate on the filter surface. Occasional back purging without removing the probes could also be used to prevent clogging.

The probes shown in Figure 23 represent a very practical way to perform multiple point sampling, especially in continuous monitoring applications. Since only a single outlet line is involved, they would be no more difficult to use than single point probes. The validity of the approach was verified by the work described in Section 4, which showed that spatial gas sampling is just as accurate for most purposes as flow proportional sampling. This means that the probes only need to be designed to insure that the same amount of sample is drawn through each orifice, which is easy to do. There is no requirement to account for velocity variations along the line of interest. The probes in Figure 23 are all line averaging devices, which makes them exactly the type of probe desired for measurements in circular ducts using the tangential method, and in rectangular ducts using the Row Average Method.



A - PARTICULATE REMOVED BY IN-LINE FILTER

B,C - PARTICULATE REMOVED BY FILTER AT PROBE INLET

NOMINAL PRESSURE DROP ACROSS INLET = 20 TORR

Figure 23. Multiple point gas sampling probes

5.2.3 Sample Trains

Two types of gas sampling have been mentioned in this report: quantitative sampling, where the desired output is a single number, such as $\dot{m}_i$, and investigative sampling, where the desired output is a concentration map. Sampling trains which use continuous gas analyzers can perform both types of sampling, while wet chemistry trains are usually practical only for quantitative sampling since evaluation of each individual sample would be too tedious. Manual traverses using wet chemistry methods can be made easier by using the spatial sampling approach. By using a constant sampling flowrate and sampling time at each point, the need for continued flow rate adjustment and a dry gas meter disappears.

One of the most common problems with continuous gas analyzers is calibration shifts, which can be as high as several percent over a period of a few hours. It is imperative that these instruments be used in strict accordance with the manufacturer's specified procedures. For manual traverse work, zero and span readings should be taken at the beginning and end of each work shift, and systematic calibration changes should be accounted for during data reduction. Calibration gases should be selected and used in accordance with manufacturer's specifications to avoid errors. For example, an SO_2 analyzer may have a very different response to a calibration gas which consists of 1000 ppm of SO_2 in air than to a gas which consists of 1000 ppm of SO_2 in nitrogen.

5.3 PROTOTYPE CONTINUOUS MONITORING SYSTEM

The complexity of continuous monitoring systems is clearly a function of the required system performance. At a minimum, a given system should provide continuous data for $\bar{\mu}_i$ for at least one gas, such as SO_2. The next step would be to provide a volumetric flow measurement capability, which would then add $\dot{m}$, $\dot{m}_i$, and $\dot{V}_s$. For environmental purposes, $\dot{m}_i$ will usually be the most desirable parameter, since a measurement in mass per unit time can be easily combined with other data to give information such as grams of SO_2 per kilogram of fuel or grams of SO_2 per kilowatt produced in a power plant. More sophisticated systems would measure outputs of additional gases, such as O_2 for control of excess air.

A full monitoring system for use in a combustion stream is shown in Figure 24, and nominal prices for system components are given in Table 7. Of the items mentioned, only the multiple port gas sampling probe is not presently commercially available. Specific manufacturers and model numbers are given only to demonstrate that the equipment does exist. Their mention does not constitute a recommendation except for the Ellison and Ramapo probes, which TRW has specifically evaluated for EPA. It is clear from Table 7 that the bulk of the cost for a continuous system is for the out-of-stream components. Also, the out-of-stream components will be almost identical regardless of whether single or multiple point techniques are used. The cost of a multiple point measurement system may be perhaps 10% higher than that of a single point system, but the accuracy of the multiple point system may be better by as much as a factor of three.

Recent improvements in small computers offer a precise calculation capability not previously achievable. The most common current practice is to record instrument outputs directly, as for μ_i or $\bar{\mu}_i$. Proper calculation of $\dot{m}$, $\dot{m}_i$, or $\dot{V}_s$, as given in equation 20 in Table 1, cannot be done without processing the outputs of several instruments. The MITS Altair data processor mentioned in Table 7 is inexpensive enough to be cost effective in a continuous monitoring system, and has the capability to perform the calculations required by equation 20. This type of data processing capability is required to maintain system accuracy. It would be impractical to record data and process it by hand or even by computer at a later time.

Approximate labor requirements to acquire, install, and use a continuous monitoring system are shown in Table 8. The ranges are necessarily very broad due to the large number of variables involved, and so the numbers should only be taken as a very general guide. The specific tasks called out will usually apply for any given system, and the distribution of hours among the individual tasks is considered representative. Since the daily time requirements for normal system operation become the largest manpower cost factor over a long period of time, it is essential to properly design the system initially so that the maintenance time requirement will be minimized. Proper system utilization also requires that a carefully written operational procedure be produced to optimize the maintenance schedule, minimize component degradation, and preserve system accuracy.

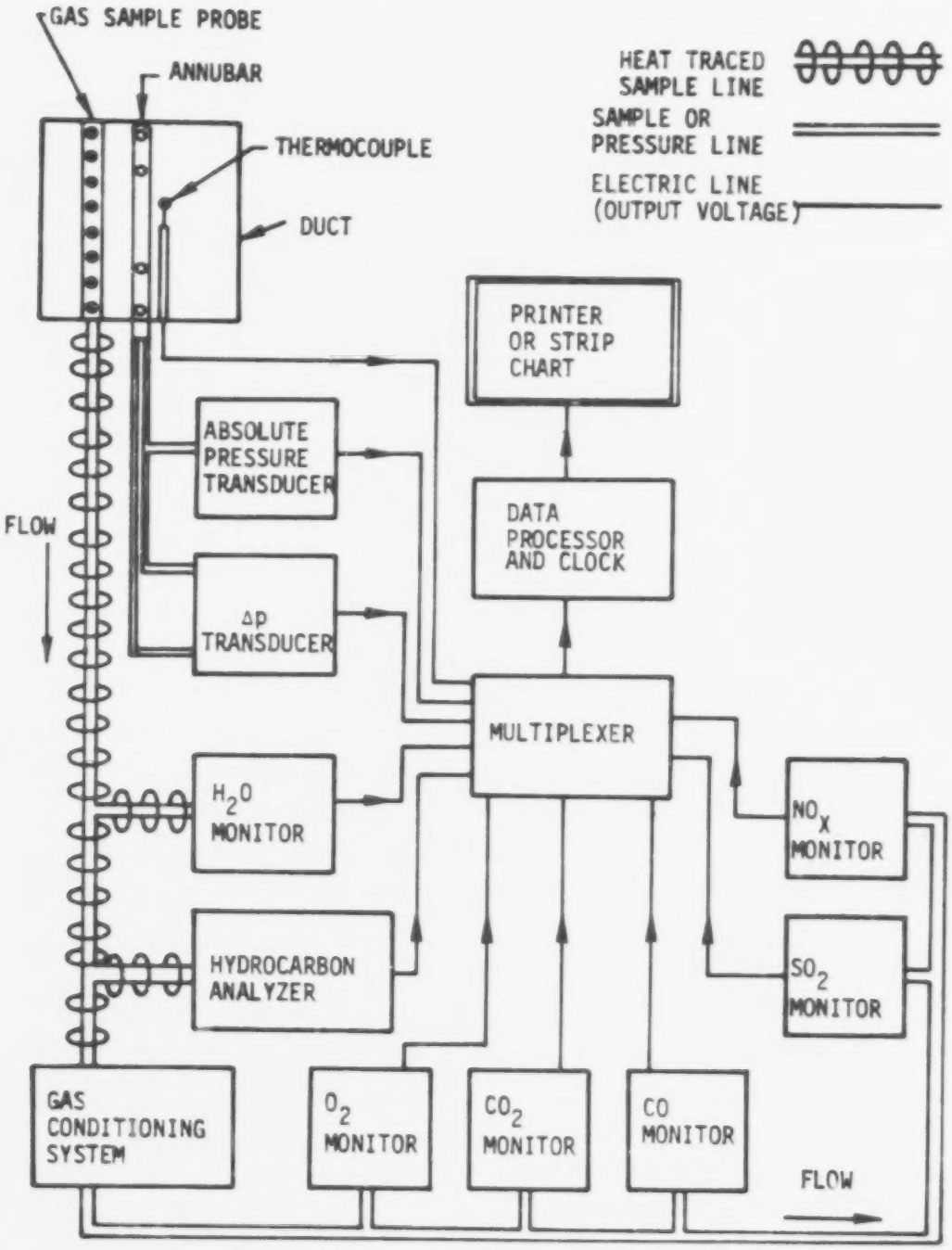


Figure 24. Schematic of a complete continuous monitoring system for a combustion process stream

Table 7. ESTIMATED CONTINUOUS MEASUREMENT SYSTEM HARDWARE COSTS

COMPONENT	ESTIMATED COST
VELOCITY MEASUREMENT	
Probes	
Ellison Annubar (5m length)[1]	$1000
Ramapo Fluid Drag Meter (5m length)	2500
Pitot-Static Probe for reference traverses	300
Support Equipment	
Thermocouple and Cold Junction (Omega-CJ)	150
Differential Pressure Transducer	
Baratron 145B(±10 torr, high accuracy)	2800
Statham PM5TC(±7 torr, medium accuracy)	400
Absolute Pressure Transducer	
Statham P822(0-800 torr)	400
Traversing Mechanism for Ramapo probe	~1500
GAS COMPOSITION MEASUREMENT	
Probes	
Multiple point probe (5m length)[1]	~1500
Single point probe for manual traverses	200
Continuous Gas Conditioning System(Beckman)	6000
Gas Analyzers	
O_2 Taylor OA 138	1000
CO_2 Beckman 865	3300
CO	3300
NO	3300
SO_2	3300
H_2O Beckman 865	3300
Hydrocarbon Beckman 402	6500
DATA HANDLING, REDUCTION, AND PRINTOUT	
MITS Altair 8800 plus support equipment	2000

[1] cost a direct function of probe length

Table 8. ESTIMATED CONTINUOUS MEASUREMENT SYSTEM LABOR REQUIREMENTS

ACTIVITY*	ESTIMATED LABOR*, HOURS	
	ENGINEERING	TECHNICIAN
ACQUISITION (Total)	(108-284)	(52-124)
Formulation of requirements	16-40	0
Site selection	8-16	0
Preliminary measurements for instrument scaling	4-8	8-16
System design and component selection	40-120	16-32
Equipment purchase	20-40	8-16
Instrument checkout	20-60	20-60
INSTALLATION (Total)	(88-336)	(104-344)
Manual traverses for in-stream component location	8-16	16-40
System integration, installation, and checkout	20-120	40-200
Manual traverses for in-place calibration	20-80	40-80
Writing of operational procedure	40-120	8-24
USE (Total)	(108-440)/yr	(533-1498)/yr
System checkout(daily)	0	1-2
Data review(weekly)	1-4	1-4
Calibration check by manual traverse(monthly)	4-16	8-40
General refurbishing(annual)	8-40	20-80

*Assumes that system measures total volumetric flow and at least one gas species concentration

As was shown in Table 3, a reasonable target for accuracy of a continuous system is a 2σ uncertainty of $\pm 9\%$ for $\dot{m}$, $\dot{m}_f$, and $\dot{V}_s$, and $\pm 5\%$ for $\bar{\mu}_f$. These uncertainties apply to individual measurements. Over a period of time, it is expected that the average values would have a smaller error. For example, for measurements of $\dot{V}_s$ on a continuous basis at a coal fired power plant as described in Reference 1, agreement between the monitoring system value and the value calculated from plant operating conditions (monitored in the control room) was on the order of $\pm 3\%$ over a 24 hour period. When the system uncertainties are truly random, they are expected to oscillate about the true mean value, so that system accuracy over a period of time such as a day or a week would be expected to be better than the single measurement uncertainty.

6. PROTOTYPE CONTINUOUS MONITORING PROCEDURES

This section presents recommended general procedures for installation of continuous monitoring systems. The recommendations are based upon the methodology and hardware discussed in Sections 4 and 5, and the equations derived in Section 2. The procedures are a self-contained unit, and may be used apart from the remainder of the manual. The purpose of the procedures is to show the kind and extent of activities which are required to install and calibrate a continuous monitoring system.

PROCEDURE 1

FLOW AND GAS COMPOSITION MEASUREMENTS IN CIRCULAR DUCTS

1. Site Selection. When possible, select the sampling plane so that 80% of the local straight run is upstream of the sampling plane. Select two orthogonal diameters in the sampling plane. If the upstream flow disturbance involves a change in direction, such as an elbow, one of the diameters should be in the plane of the disturbance.

2. Survey Traverses. Perform survey traverses for velocity and gas composition at as many plant operating conditions as is feasible. Operating conditions must remain constant during each traverse. Forty point traverses should be performed (10 points per radius) using the Log Linear Method for velocity and the tangential method for gas sampling, as given in Table 1-1.

TABLE 1-1

POINT LOCATIONS FOR SURVEY TRAVERSES, IN PERCENT OF DUCT DIAMETER FROM INSIDE WALL TO TRAVERSE POINT

Point	1	2	3	4	5	6	7	8	9	10
Log Linear	.82	4.4	6.5	9.9	12.7	16.8	20.1	25.4	29.9	40.2
Tangential	1.3	3.9	6.7	9.7	12.9	16.5	20.4	25.0	30.6	38.8

A standard pitot-static probe should be used for the velocity traverse. Reduce the velocity data using equation 1.1.1 from the appendix and plot velocity and composition data as a function of distance. Compute gas stratification levels.

3. Equipment Selection and Installation. Select and acquire hardware for the continuous monitoring system. If the gas stratification level is too high to permit single point sampling, use a multi-port probe or equivalent. If a point sampling velocity technique is selected, points along both diameters should be selected in accordance with the Log Linear 4 technique shown in Table 1-2. For gas sampling, eight points should be selected along one diameter according to the tangential method in Table 1-3. The diameter selected for gas sampling should be the one along which the greatest variation in composition is measured during the survey traverses.

TABLE 1-2

LOG-LINEAR 4 METHOD FOR VELOCITY MEASUREMENT, LOCATION IN PERCENT OF DUCT DIAMETER FROM INSIDE WALL TO SAMPLE POINT

Point	1	2	3	4
Location	4.3	29.0	71.0	95.7

TABLE 1-3

TANGENTIAL METHOD FOR GAS SAMPLING, LOCATION IN PERCENT OF DUCT DIAMETER FROM INSIDE WALL TO SAMPLE POINT

Point	1	2	3	4	5	6	7	8
Location	3.3	10.5	19.4	32.3	67.7	80.6	89.5	96.7

If an Annubar is selected as the flow sensor, it should be installed along the diameter which showed the greatest variation during the survey traverse. If the Annubar and gas sample probe are to be installed along the same diameter, the gas sample probe should be located at least 15 cm downstream of the Annubar and 3 cm to one side. If they are on different diameters, the gas sample probe should be at least 15 cm downstream of the Annubar. The system should be installed and made operational.

4. In Place Calibration. The continuous monitoring system should be calibrated in place using 16 point Log-Linear velocity traverses, given in Table 1-4, and 16 point gas sample traverses using the tangential method in Table 1-3.

TABLE 1-4

LOG LINEAR 8 METHOD FOR VELOCITY TRAVERSES, LOCATION IN PERCENT OF DUCT DIAMETER FROM INSIDE WALL TO SAMPLE POINT

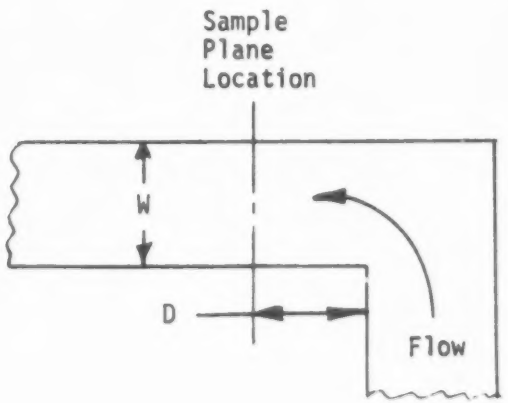
Point	1	2	3	4	5	6	7	8
Location	2.1	11.7	18.4	34.5	65.5	81.6	88.3	97.9

Calculate volumetric flow according to Appendix equation 1.1.2 and species emission from Appendix equation 1.2.4. Using monitoring system outputs obtained during or before and after each traverse, solve Appendix equations 2.1 and 2.3 for the calibration factors. Program the calibration factors into the data processor, and the system is ready for use.

PROCEDURE 2

FLOW AND GAS COMPOSITION MEASUREMENTS IN RECTANGULAR DUCTS

1. Site Selection. The preferred sampling location is downstream of a mitered elbow. If this type of location is not available, select the sampling plane so that 80% of the local straight run is upstream of the sampling plane. For the elbow case, the sample plane should be selected in accordance with Figure 2-1.



A. For Systems Using Annubar, $D = 1.5W \begin{smallmatrix}+.25W\\-.75W\end{smallmatrix}$

B. For Systems Using Row Average Method for Velocity $D = .8W \begin{smallmatrix}+.40W\\-.60W\end{smallmatrix}$

Figure 2-1. Recommended sample plane locations downstream of a rectangular elbow

2. Survey Traverses. Perform survey traverses for velocity and gas composition at as many plant operating conditions as is feasible. Operating conditions must remain constant during each traverse. Traverse should be performed using an n x n matrix with $6 \leq n \leq 8$, using the centroid of equal areas technique as illustrated for a 4 x 4 matrix in Figure 2-2.

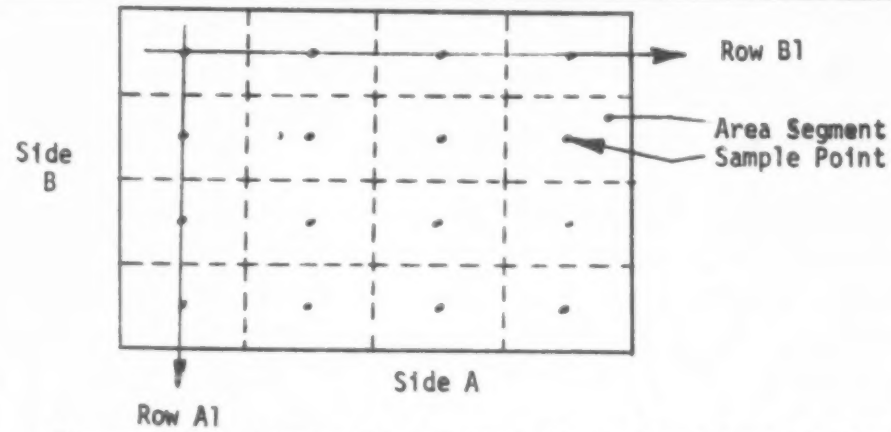


Figure 2-2. Illustration of Centroid of Equal Areas Technique for Rectangular Ducts

A standard pitot-static probe should be used for the velocity traverses. Reduce the velocity data using Appendix equation 1.1.1. Compute the volumetric flow rates from Equation 1.1.2 and the average mole fractions from 1.2.1 or 1.2.2, and the gas stratification levels.

3. Equipment Selection and Installation. Select the instruments to be used. If single point gas sampling is not acceptable and/or the Row Average Method or Annubar is to be used, the survey traverse data must be examined to determine the required probe length (equal to the length of side A or B in Figure 2-2). Compute the average velocity and/or concentration as required along each row, as identified in Figure 2-2, for each traverse and normalize the row average with respect to the overall average. Plot the results versus distance as shown in Figure 2-3.

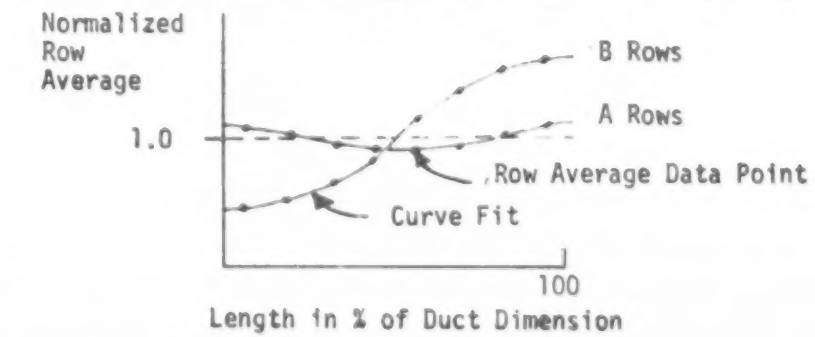


Figure 2-3. Typical plot of normalized row averages

When possible, a row for actual sensor installation should be selected from the smoother of the curves (the A curve in Figure 2-3) since more repeatable data will be obtained in that direction. For the case in Figure 2-3, the preferable row would be an A row, meaning that the probe length would be equal to that of side B. In the case of velocity measurements downstream of an elbow, the desired row direction will be in the plane of the elbow.

Once the row direction has been chosen, the actual row location must be selected. The Annubar should always be placed in the middle of the duct. For the Row Average Methods, if four or more survey traverses have been performed, select the row location at which the best normalized row average repeatability was achieved. For three or less traverses, select the row location at which the normalized row average was closest to unity.

Obtain and install system hardware and activate the system. A multiport gas sample probe, if used, should have 8 equally spaced ports.

4. In Place Calibration. The continuous monitoring system should be calibrated in place using 4 x 4 traverses as illustrated in Figure 2-2. Calculate volumetric flow according to Appendix equation 1.1.2 and species emission from Appendix equation 1.2.4. Using monitoring system outputs obtained during or before and after each traverse, solve Appendix equations 2.1 and 2.3 for the calibration factors. Program the calibration factors into the data processor, and the system is ready for use.

APPENDIX
FLOW AND GAS SAMPLE CALCULATIONS

1. MANUAL TRAVERSES

1.1 FLOW TRAVERSE USING PITOT-STATIC PROBE

1.1.1 Point Velocity at Standard Conditions

$$u_s = \frac{T_s}{p_s}\sqrt{\frac{2Rp_\infty \Delta p}{MT_\infty}} = 49.74\sqrt{\frac{p_\infty \Delta p}{MT_\infty}} \quad , \frac{m}{sec}$$

where

u_s = velocity at standard conditions, $\frac{m}{sec}$

T_s = standard temperature, 760 torr

p_s = standard pressure, 293.16°K

R = universal gas constant, 8314.32 $\frac{gm\ m^2}{mole\ sec^2 °K}$

p_∞ = static pressure, torr

Δp = differential pressure from pitot-static probe, torr

M = average molecular weight(wet), $\frac{gm}{mole}$

T_∞ = static temperature, °K

1.1.2 Volumetric flow at standard conditions

$$\dot{V}_s = \bar{u}_s\ A = \frac{AT_s}{Np_s}\sqrt{\frac{2Rp_\infty}{M}}\sum_{n=1}^{N}\sqrt{\frac{\Delta p_n}{T_{\infty_n}}}$$

or

$$\dot{V}_s = 49.74\ \frac{A}{N}\sqrt{\frac{p_\infty}{M}}\sum_{n=1}^{N}\sqrt{\frac{\Delta p_n}{T_{\infty_n}}}\ , m^3/sec$$

where

$\dot{V}$ = total volumetric flow at standard conditions, m^3/sec

A = duct cross-sectional area, m^2

N = total number of traverse points

1.1.3 Total Gaseous Mass Flow Rate

$$\dot{m} = \frac{P_s}{RT_s} \bar{M} \dot{V}_s = \frac{A}{N} \sqrt{\frac{2M_{D_m}}{R}} \sum_{n=1}^{N} \sqrt{\frac{\Delta p_n}{T_{m_n}}}$$

or

$$\dot{m} = 2067.8 \frac{A}{N} \sqrt{MP_m} \sum_{n=1}^{N} \sqrt{\frac{\Delta p_n}{T_{m_n}}} \quad , \text{gm/sec}$$

where

$\dot{m}$ = total gaseous mass flow rate, gm/sec

1.2 GAS SAMPLE TRAVERSE

1.2.1 Average Species Mole Fraction, Dry

$$\bar{\mu}_{i_D} = \frac{1}{N} \sum_{n=1}^{N} (\mu_{i_D})_n$$

where

μ_{i_D} = point mole fraction, dry, $\frac{\text{moles i}}{\text{mole of dry mixture}}$

$\bar{\mu}_{i_D}$ = average mole fraction, dry, $\frac{\text{moles i}}{\text{mole of dry mixture}}$

1.2.2 Average Species Mole Fraction, Wet

$$\bar{\mu}_{i_w} = \frac{1}{N} \sum_{n=1}^{N} (\mu_{i_w})_n$$

or

$$\bar{\mu}_{i_w} = (1-\bar{\mu}_{H_2O})\bar{\mu}_{i_D}$$

where

μ_{i_w} = point mole fraction, wet, $\frac{\text{moles i}}{\text{mole of wet mix}}$

$\bar{\mu}_{i_w}$ = average mole fraction, wet, $\frac{\text{moles i}}{\text{mole of wet mix}}$

1.2.3 Average Molecular Weight in a Combustion Stream

$$M = (1-\bar{\mu}_{H_2O})\left[32\bar{\mu}_{O_2_D} + 44.01\bar{\mu}_{CO_2_D} + .04 + 28.01\left(.99-\bar{\mu}_{O_2_D}-\bar{\mu}_{CO_2_D}\right)\right] + 18.01\bar{\mu}_{H_2O}$$

1.2.4 Gaseous Species Average Mass Flow Rate

$$\dot{m}_i = \dot{m}\,\frac{M_i}{M}\,\bar{\mu}_{i_w} = \frac{AM_i}{N}\sqrt{\frac{2p_\infty}{MR}}\left(\sum_{n=1}^{N}\sqrt{\frac{\Delta p_n}{T_{\infty n}}}\right)\bar{\mu}_{i_w}$$

or

$$\dot{m}_i = 2067.8\,\frac{AM_i}{N}\sqrt{\frac{p_\infty}{M}}\left(\sum_{n=1}^{N}\sqrt{\frac{\Delta p_n}{T_{\infty n}}}\right)\bar{\mu}_{i_w}\ ,\ \text{gm/sec}$$

where

$\dot{m}_i$ = species mass flow rate, gm/sec

M_i = molecular weight of species i, gm/mole

2. CONTINUOUS MONITORING

2.1 VOLUMETRIC FLOW AT STANDARD CONDITIONS

2.1.1 Annubar as Flow Sensor

$$\dot{V}_s = 49.74AK_A\sqrt{\frac{p_\infty \Delta p_A}{M\,T_A}}\ ,\ m^3/sec$$

where

K_A = Annubar calibration factor (nominal .65)

Δp_A = Annubar differential pressure, torr

T_A = Representative stream temperature, °K

2.1.2 Point Sensor Array or Automatic Traversing Point Sensor; Ramapo Fluid Drag Meter Used as Example

$$\dot{V}_s = 49.74AK_R\sqrt{\frac{p_\infty}{M}}\sum_{n=1}^{N}\sqrt{\frac{V_{R_n}}{T_{\infty n}}}\ ,\ m^3/sec$$

where

K_R = Ramapo calibration factor

V_R = Ramapo voltage ratio, dimensionless

N = total number of points used (8 nominal)

2.2 Total Gaseous Mass Flow Rate

$$\dot{m} = 41.57\ M\ \dot{V}_s \quad , \text{gm/sec}$$

2.3 Species Mass Flow Rate

$$\dot{m}_i = \dot{m}\left(\frac{M_i}{M}\right)\bar{\mu}_{i_w} K_{w_i} \quad , \text{gm/sec}$$

where

K_{w_i} = continuous system species calibration factor; ideally $K_{w_i} = 1$

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GLOSSARY

SYMBOL	USAGE	DIMENSIONS
A	area	m^2
C	constant	dimensionless
D	diameter	m
f	functional relationship	--
G	general parameter	--
H	general variable	--
I	total number of gas species	--
K	calibration factor	dimensionless
ℓ	length	m
M	molecular weight	gm/mole
$\dot{m}$	mass flow rate	gm/sec
N	total number of area segments	dimensionless
$\vec{n}$	unit normal vector	dimensionless
p_o	stagnation pressure	torr
p_∞	static pressure	torr
Δp	differential pressure	torr
R	universal gas constant	$\frac{gm\ m^2}{mole\ sec^2\ ^\circ K}$
T_∞	static temperature	$^\circ K$
U	magnitude of velocity vector	m/sec
$\vec{u}$	velocity vector	m/sec
u	axial velocity component	m/sec
$\dot{V}_s$	total volumetric flowrate at standard conditions	m^3/sec
X	general parameter	--
x	length	m
y	length	m
θ	flow orientation angle	radians
μ_i	mole fraction	moles of i/mole
ρ	gas density	gm/m^3
σ	standard deviation	--

GLOSSARY (Cont'd)

SYMBOL	USAGE	DIMENSIONS
σ_{SE}	total system uncertainty	percent
σ_{SPE}	single point measurement uncertainty	percent
σ_{AE}	assumption uncertainty	percent
σ_{ME}	mapping uncertainty	percent
σ_{TE}	temporal uncertainty	percent
$\overline{(\ )}$	mean value	--
$(\ )_i$	value of parameter for gas species $_i$	--
$(\ )_n$	mean value of parameter in area segment n	--